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TECHNICAL NOTE

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PERFORMANCE OF A DOUBLE-ROW RADIAL AIRCRAFT ENGINE
WITH THREE METHODS OF SAFETY-FUEL INJECTION

By Donald J. Michel, Robert O. Hickel
and Charles H. Voit

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SUMMARY

An investigation was made to determine whether a safety fuel with a flash point of 122° F could be successfully used in a high-power radial aircraft engine without individual cylinder fuel-injection equipment. The safety fuel was injected into the combustion-air stream by (1) the NACA injection impeller, (2) the NACA impinging-jets nozzle bar, and (3) the standard nozzle bar. Fuel-air ratios of the individual cylinders were determined for a range of engine powers from 1200 to 1800 brake horsepower. The effect of average fuel-air ratio and combustion-air temperature on mixture distribution was studied. The distribution patterns produced by the various methods of injecting safety fuel were compared with the results obtained when gasoline of grade 100/130 was injected by the standard nozzle bar. Comparisons of the required manifold pressure, combustion-air flow, and brake specific fuel consumption for the three methods of safety-fuel injection and the standard method of injecting gasoline were also made.

Satisfactory mixture distribution of safety fuel resulted when the NACA injection impeller was used but when either the NACA impinging-jets nozzle bar or the standard nozzle bar was used, the mixture distribution was unsatisfactory. Throughout the range of engine powers, average fuel-air ratios, and combustion-air temperatures investigated, the injection impeller produced better mixture distribution of safety fuel than did the standard method of injecting gasoline. The mixture distribution obtained with safety fuel injected by the injection impeller was affected less by changes in engine power, average fuel-air ratio, and combustion-air temperature than that obtained with the other methods of injection. The poor distribution that resulted when safety fuel was injected by the NACA impinging-jets nozzle bar or standard nozzle bar considerably reduced the maximum power output of the engine and restricted the lower limits of the average fuel-air ratio and combustion-air temperature at which the engine would operate steadily.

Between 1200 and 1600 brake horsepower the required absolute manifold pressure and combustion-air flow ranged from 1.5 to 6.0 percent more for the three methods of safety-fuel injection than for the standard method of injecting gasoline. The injection impeller required less manifold pressure and combustion-air flow than did the other methods of injecting safety fuel. The brake specific fuel consumption at 1200 brake horsepower for all methods of safety-fuel injection was about 6 percent higher than for standard injection of gasoline. Idling characteristics of the engine with safety fuel were satisfactory but starting with the engine either warm or cold was impossible when a fuel with a flash point of 122° F was used. Starting was accomplished with a warm engine, however, using a fuel with a flash point of 99° F.

INTRODUCTION

The replacement of aviation gasoline with a fuel that would reduce or eliminate the fire hazard in aircraft has long been needed. Gasoline, with a flash point of about -30° F, gives off highly inflammable vapors under almost all climatic conditions. Low-volatility fuels (commonly called safety fuels) are generally regarded as those fuels with a flash point of over 105° F; because of high flash points, safety fuels should reduce the fire hazard. Safety fuels with properties such as octane rating, heating value, and gum content that compare favorably with the properties of standard aviation gasoline can be manufactured.

Single-cylinder investigations of safety fuel introduced directly into a cylinder through an injection nozzle showed that safety fuel could be successfully used in a reciprocating engine if the fuel were properly introduced into the cylinder (references 1 and 2). These investigations also showed that the power output and the fuel economy of the engine using safety fuel was about equal to that obtained with gasoline. If the complexities of a direct cylinder fuel-injection system are to be avoided when using safety fuel, the fuel must be finely dispersed in the combustion-air stream to facilitate rapid vaporization of the fuel. The amount of dispersion necessary for successful use of safety fuel depends principally upon the temperature, the velocity, and the turbulence of the air stream where the fuel is introduced.

Two relatively simple methods, namely the NACA injection impeller and the NACA impinging-jets nozzle bar, have been developed by the NACA for injecting fuel into the combustion-air system before the air enters the individual intake pipes. The NACA injection impeller (reference 3) injects finely dispersed fuel into the

combustion-air stream near the impeller exit; whereas the NACA impinging-jets nozzle bar introduces finely atomized fuel into the air stream immediately downstream of the carburetor. When both these methods were applied to an 18-cylinder, radial aircraft engine using gasoline, the mixture distribution was considerably improved as compared with the distribution of the standard-nozzle-bar injection. The difference between the value of the maximum and the minimum fuel-air ratio of the engine for a given power was reduced to about one-third its value with the standard-nozzle-bar injection. There was a possibility that either the NACA impinging-jets nozzle bar or the NACA injection impeller could produce satisfactory mixture distribution when safety fuel was used. Either of these methods would eliminate the need for complex individual cylinder-injection equipment.

The three methods of safety-fuel injection investigated at the NACA Cleveland laboratory and reported herein are (1) NACA injection impeller, (2) standard nozzle bar, and (3) NACA impinging-jets nozzle bar. Fuel-air-ratio and temperature-distribution patterns are presented for each type of safety-fuel injection and are compared with the patterns obtained with a standard engine operating with gasoline. The engine was operated over a range of engine cruising powers and speeds normally used in flight. The effect of average engine fuel-air ratios and carburetor-air temperatures on the mixture distribution of the safety fuel at a low cruising power is also presented. The starting and the idling characteristics of the engine were also investigated with two safety fuels of different flash points.

FUELS

A comparison of the physical properties of aviation gasoline and the safety fuel used for this investigation is presented in the following table:

Property	Gasoline	Safety fuel
Grade	100/130	106/139
Tetraethyl lead content, ml/gal	4.55	4.63
Flash point, closed cup, °F	Below -30	122
Distillation range, °F:		
Initial boiling point	108	320
10-percent evaporated	141	334
50-percent evaporated	205	346
90-percent evaporated	255	362
Final boiling point	332	384
Freezing point, °F	Below -76	Below -76
Reid vapor pressure at 100° F, lb/sq in.	7	0.1
Residue, copper dish, mg/100 ml	2.0	2.0
Accelerated gum content, mg/100 ml	2.3	2.0
Accelerated gum precipitate, mg/100 ml	0.2	0.6
Sulfur content, percent	0.012	0.0001
Heating value, Btu/lb	18740	18650
Hydrogen-carbon ratio	0.166	0.165
Specific gravity at 60° F	0.719	0.782

For this investigation the flash point and distillation range are of the greatest importance. The flash point of a fuel is the lowest temperature at which an open flame will flash the fuel; this flash point is one indication of the extent of the fire hazard in each fuel. The distillation temperatures indicate the vaporization characteristics of the fuel and thus provide an indication of the ease with which an engine may be expected to start and also an indication of the rate of flame spread.

Investigation of the starting characteristics of the engine was also made with another safety fuel having a flash point of 99° F, which is somewhat lower than that normally considered a minimum for fuels classified as safety fuels. Hereinafter, the fuel with a flash point of 122° F will be designated safety fuel A and the fuel with a flash point of 99° F, as safety fuel B. The distillation curves of the two safety fuels are compared with gasoline (grade 100/130) in figure 1. Because safety fuel B, which is a blend of safety fuel A, xylene, and S-4 reference fuel, was used only for starting tests, only the flash point and the distillation curve are presented

METHODS OF FUEL INJECTION

NACA injection impeller. - A sketch of the injection impeller used in this investigation is shown in figure 2. The impeller incorporates fuel-injection passages 1/16 inch in diameter that discharge into alternate impeller air channels. The fuel-injection passages are slightly inclined from a radial position toward the advancing side of the impeller blade so the fuel droplets are struck and dispersed by the impeller blade. The NACA injection impeller discharges the fuel near the impeller tip in a region where the air is relatively hot and the velocity is high. A more complete description of the injection impeller is given in reference 3.

Standard nozzle bar. - The standard nozzle bar ejects fuel at a point immediately downstream of the throttles from 24 orifices located in the bar, as shown in figure 3(a). The fuel is discharged from relatively large orifices and from less than half the length of the bar with the result that the stream of fuel is not finely atomized and covers only part of the combustion-air duct. Both of these factors limit the dispersion and vaporization of the fuel in the combustion-air system between the carburetor and the supercharger inlet.

NACA impinging-jets nozzle bar. - The NACA impinging-jets nozzle bar (fig. 3(b)) ejects fuel from 16 pairs of orifices located the entire length of the bar. The orifices in each pair are so located at right angles to each other that the sprays impinge to form a finely atomized mist of fuel. The larger orifices (0.052-in. diameter) that are along one side of the bar permit about two-thirds of the fuel to be discharged from the side of the bar closest to the upper portion of the supercharger impeller in an attempt to compensate for the tendency of liquid fuel to travel toward the lower section of the impeller.

In order to obtain the proper fuel flows with the impinging-jets nozzle bar, the fuel pump pressure had to be increased from the standard value of 17 pounds per square inch to 25 pounds per square inch.

APPARATUS

Engine and test cell. - The investigation was made with an 18-cylinder, double-row, radial, air-cooled aircraft engine having a normal rating of 2000 brake horsepower at 2400 rpm and a take-off rating of 2200 brake horsepower at 2600 rpm. The engine has a

single-stage, gear-driven supercharger with a gear ratio of 6.06:1. The installation of the engine in the test cell is shown in figure 4.

Power was absorbed by a hydromatic, four-bladed, constant-speed propeller, 16 feet, 7 inches in diameter, and measured by a calibrated torquemeter incorporated in the engine nose section. An injection-type hydrometering carburetor was used as a fuel-metering device. Combustion-air was provided by a system similar to that described in reference 3, and the pressure and the temperature at the carburetor deck were controlled by an external system. The engine was fitted with a ring cowl and cooling-air was drawn over the engine by a controllable exhaust system. The individual cylinders exhausted directly to the atmosphere through relatively short exhaust stacks.

Instrumentation. - Temperatures were measured on each cylinder at the rear-spark-plug gasket and exhaust-valve seat, as shown in figure 5. Throughout the investigation, the exhaust-valve-seat temperature of cylinders 1, 16, and 18 were not recorded because of faulty thermocouples. Cooling-air temperature was measured by three thermocouples equally spaced around the cowl inlet. Combustion-air temperature was measured by three thermocouples located at the carburetor screen immediately upstream of the carburetor.

The fuel-air ratios of the individual cylinders were determined by exhaust-gas analysis. Exhaust-gas samples were obtained from the engine exhaust stacks in the manner described in reference 3 and were analyzed by the NACA mixture analyzer described in reference 4. In this investigation, the fuel-air ratio was measured on a millivoltmeter calibrated by Orsat analysis for each type of fuel used. Periodic oxygen-dilution surveys were made of each cylinder to determine the leakage of air into the exhaust stacks from the atmosphere; the fuel-air ratios were corrected for any oxygen dilution. A maximum dilution of 2 percent, which gave a fuel-air-ratio correction factor of 1.084, was observed at an engine power of 2000 brake horsepower.

The absolute manifold pressure was measured in the supercharger collector. The carburetor-deck pressure was measured by a static-pressure tube at the upper carburetor deck. Combustion-air flow was calculated from the measurement of the venturi-suction differential pressure and the air-flow calibration curve of the carburetor. The fuel flow to the engine was measured by rotameters.

PROCEDURE

Data were taken to evaluate the mixture distribution among cylinders, the temperature variation from cylinder to cylinder, the engine manifold pressure, and the combustion-air flow for a given engine condition. Runs were made at four cruising powers and speeds, approximating a propeller load curve normally used in flight. Runs at several fuel-air ratios and combustion-air temperatures were also made at a low cruising power. The runs were made for the standard engine using gasoline and repeated for each of the three injection methods using safety fuel. The engine was operated at the following conditions:

Run series	Engine power (bhp)	Engine speed (rpm)	Approximate average fuel-air ratio	Combustion-air temperature ($^{\circ}$ F)
I	1200	2000	0.070	100
	1400	2100	.082	100
	1600	2200	.087	100
	1800	2300	.091	100
II	1200	2000	Varied	100
III	1200	2000	0.068	Varied

For all points, the existing atmospheric pressure was maintained at the carburetor deck. All cylinder temperatures were corrected to a constant cooling-air temperature of 50° F (a mean value of the cooling-air temperatures) by the method presented in reference 5.

Runs of series I are hereinafter called the runs at standard powers. The fuel flow at each power was set within the limits specified by the engine manufacturer. The cooling-air flow was set to limit the hottest rear-spark-plug-gasket temperature to approximately 450° F.

In the runs of series II, the fuel flow was reduced in successive steps from the automatic-rich position until unstable engine operation resulted. These runs were made with a constant cooling-air flow determined by the amount of air flow required to limit the maximum rear-spark-plug-gasket temperature to a value below 450° F at a fuel-air ratio giving the maximum temperature.

The runs of series III were made at the highest and the lowest combustion-air temperature obtainable with the test-cell equipment. The lowest temperature when operating with the NACA impinging-jets nozzle bar or the standard nozzle bar and safety fuel was limited by stable engine operation at the specified fuel flow. The cooling-air flow was maintained constant throughout this series of runs.

Engine starts were investigated by starting the engine with safety fuels A and B when the engine was warm and then when the engine was cold.

RESULTS AND DISCUSSION

The three methods of injecting safety fuel were evaluated by comparing the resulting mixture-distribution patterns with those produced by the standard nozzle-bar injection of gasoline. Because cylinder temperatures are considerably influenced by the fuel-air ratio, the cylinder temperature-distribution patterns are presented to substantiate the general trends of the mixture-distribution patterns. Because temperatures are of secondary importance in this investigation, temperature-distribution patterns are shown only for the four standard powers.

Standard Powers

Mixture distribution. - Mixture-distribution patterns for the four standard powers and engine speeds (series I) are shown in figure 6. For each power, the distribution patterns produced by the three methods of injecting safety fuel are compared with the patterns produced by the standard nozzle-bar injection of gasoline, hereinafter referred to as the standard engine. In the standard engine, cylinders 2 to 6 generally operate relatively lean and cylinders 10 to 16 operate rich; the same general pattern held for the range of powers. The spread in fuel-air ratio (difference between the maximum and minimum fuel-air ratios of the individual cylinders), however, tended to increase with power, the spread being 0.017, 0.024, 0.021, and 0.023 at 1200, 1400, 1600, and 1800 brake horsepower, respectively, in the standard engine.

When safety fuel was injected at 1200 brake horsepower (fig. 6(a)), the mixture-distribution pattern resulting from the use of the NACA injection impeller was similar to that produced by the standard engine. Cylinders 2 to 7 were slightly richer than in the standard engine and cylinders 9 to 18 were generally leaner than in the standard engine. The standard nozzle bar produced a pattern that

was similar to that of the standard engine for cylinders 1 to 9, whereas the left half (cylinders 10 to 18) of the engine was generally considerably leaner than the standard engine. With the NACA impinging-jets nozzle bar, the right half of the engine operated richer than the standard engine and the left half of the engine was much leaner. The fuel-air ratio spreads for the NACA injection impeller, standard nozzle bar, and NACA impinging-jets nozzle bar were 0.013, 0.021, and 0.026, respectively, as compared with 0.017 for the standard engine.

At 1400 brake horsepower (fig. 6(b)) with the injection impeller, cylinders 1 and 8 to 18 operated at a fuel-air ratio 0.007 to 0.014 leaner than the standard engine, which reduced the spread in mixture distribution to 0.013 as compared with 0.024 for the standard engine. The NACA impinging-jets nozzle bar produced a very poor mixture distribution. Cylinders 4 to 8 were much richer than the standard engine and cylinders 1 and 2 and 10 to 18 were leaner than the standard engine; cylinders 13 to 18 were the leanest, operating at fuel-air ratios ranging from 0.066 to 0.072. The spread was 0.040 for the NACA impinging-jets nozzle bar as compared with 0.024 for the standard engine. No data were taken at 1400 brake horsepower with standard nozzle-bar injection because of the limited supply of safety fuel.

For 1600 brake horsepower (fig. 6(c)), the NACA injection impeller with safety fuel resulted in a slight improvement in distribution over that of the standard engine. Cylinders 3 to 7 were richer than in the standard engine and cylinders 11 to 18 were slightly leaner. The injection impeller reduced the spread to 0.018 from 0.021 for the standard engine. The standard nozzle bar produced a very poor distribution pattern; cylinders 5, 6, and 7 were excessively rich, operating at fuel-air ratios averaging 0.113. Cylinders 1, 2, 3, and 10 to 18 were much leaner than the standard engine; cylinders 12, 13, and 14 were leanest, operating at fuel-air ratios of about 0.069. The spread was 0.052 as compared with 0.021 for the standard engine. Use of the NACA impinging-jets nozzle bar resulted in cylinders 3 to 7 operating considerably richer than the standard engine; whereas cylinders 1 and 12 to 18 were much leaner. Cylinders 13, 14, and 17 were operating at fuel-air ratios of about 0.068. The spread for the NACA impinging-jets nozzle bar was 0.037.

At 1800 brake horsepower (fig. 6(d)), the distribution patterns for the NACA injection impeller and the standard engine were similar except for cylinders 8 to 12, which operated at a fuel-air ratio 0.007 to 0.012 leaner when using the NACA injection impeller.

Use of the injection impeller and safety fuel resulted in a spread of 0.016 as compared with 0.023 for standard injection of gasoline. No patterns are shown for either the NACA impinging-jets nozzle bar or the standard nozzle bar at this power because 1800 brake horsepower was unobtainable with either of these methods. The failure to produce this power was probably caused by excessive amounts of incompletely vaporized fuel resulting in a nonuniform mixture within the cylinder. In addition, there was a nonuniform mixture distribution among the individual cylinders, making some cylinders exceedingly rich.

In general, for each power the mixture-distribution patterns produced by the NACA injection impeller with safety fuel were better than those resulting from use of the standard nozzle bar with gasoline. The NACA impinging-jets nozzle bar and the standard nozzle bar produced mixture-distribution patterns with safety fuel that resulted in much greater spreads than those produced by the standard engine. The spreads in fuel-air ratio tended to increase with an increase in power for each method of injecting safety fuel. Use of the NACA injection impeller resulted in the smallest increase in spread, from a value of 0.013 at 1200 and 1400 brake horsepower to 0.018 at 1600 brake horsepower. The spread for the standard nozzle bar was a minimum of 0.021 at 1200 brake horsepower and a maximum of 0.052 at 1600 brake horsepower. The NACA impinging-jets nozzle bar exhibited a minimum spread of 0.026 at 1200 brake horsepower and a maximum of 0.040 at 1400 brake horsepower. The mixture-distribution patterns with the NACA impinging-jets nozzle bar and the standard nozzle bar were nearly reversed from those produced by the standard engine, inasmuch as the right side of the engine was usually much richer and the left side was much leaner than the average fuel-air ratio.

Temperature distribution. - Temperature-distribution patterns for the rear spark-plug gasket and exhaust-valve seat are presented in figures 7 and 8, respectively, for each of the four standard powers. The general trends of the temperature patterns substantiate the trends of the mixture-distribution patterns with the leanest cylinders operating hottest and the richest cylinders operating coolest.

For the rear-spark-plug-gasket temperature, the best agreement between cylinder fuel-air ratio and temperature was obtained above 1200 brake horsepower. For the higher powers all cylinders usually operated above the fuel-air ratio that produced maximum cylinder temperatures (approximately 0.068). At 1200 brake horsepower, however, many cylinders were richer or leaner than the fuel-air ratio that resulted in the maximum cylinder temperature and consequently a relatively large change in fuel-air ratio may not have

greatly changed the cylinder temperatures. Reference 6 shows that variations of $\pm 20^{\circ}$ F may exist between actual and calculated cylinder temperatures even when the effects of power, fuel-air ratio, cooling-air flow, cooling-air temperature, and combustion-air temperature are accounted for. Other changes in temperature that cannot be attributed to changes in the fuel-air ratio may be caused by unaccountable variables.

The temperature spreads for the rear spark-plug gasket followed the same trends as for the fuel-air ratio with the spread generally increasing with increases in engine power and with the combination of safety fuel and NACA injection impeller producing the smallest spread (fig. 7). At 1200 brake horsepower for the standard nozzle bar and the NACA impinging-jets nozzle bar, relatively small temperature spreads (fig. 7(a)) resulted from large fuel-air ratio spreads (fig. 6(a)). This small temperature spread was caused by the shifting of the mixture-distribution pattern from that obtained with the standard engine, as shown in figure 6(a).

The exhaust-valve-seat temperatures (fig. 8) follow the same trends as the rear-spark-plug-gasket temperatures (fig. 7). Because in the front-row cylinders the exhaust port is located at the front of the cylinders and in the rear-row cylinders the exhaust port is at the rear of the cylinder, large temperature differences exist among the exhaust-valve seats for each row. For this reason, a better evaluation of the temperature distribution can be made by comparing cylinders within each row. Low temperature spreads were also produced at 1200 brake horsepower for the NACA impinging-jets nozzle bar and the standard nozzle bar although the mixture distribution was rather poor.

Although no data are presented, it was observed that with satisfactory mixture distribution approximately the same cooling-air pressure drop was required to maintain a given cylinder temperature for both gasoline and safety fuel.

Effect of Average Fuel-Air Ratio on Mixture Distribution

The effect of the average fuel-air ratio on the mixture distribution at 1200 brake horsepower for the standard engine with gasoline and for the three methods of injecting safety fuel are shown in figure 9. A change in the average fuel-air ratio from 0.063 to 0.084 for the standard engine had little effect on the shape of the mixture-distribution pattern, which remained essentially the same throughout the range of fuel-air ratios. The spread tended to increase slightly with an increase in the average fuel-air ratio, the spread being 0.018, 0.017, and 0.022 at average fuel-air ratios of 0.063, 0.071, and 0.084, respectively.

Use of safety fuel and the NACA injection impeller resulted in good mixture distribution throughout the range of average fuel-air ratios investigated. The pattern did not change appreciably with changes in the average fuel-air ratio. For each fuel-air ratio, cylinder 18 was leanest and cylinders 7 and 13 the richest. The change in fuel-air-ratio spread with changes in average fuel-air ratio was slight. The spreads were 0.014, 0.013, and 0.017 at average fuel-air ratios of 0.062, 0.071, and 0.082, respectively.

For the standard nozzle bar and safety fuel, the mixture distribution was very poor at an average fuel-air ratio of 0.068 and became increasingly worse with enrichment of the average fuel-air ratio. Throughout the range, cylinder 4 was leanest. The richest portion of the engine shifted from cylinder 9 at an average fuel-air ratio of 0.068 to cylinder 17 at average fuel-air ratios of 0.078 and 0.084. The deviation of cylinder 17 from the average fuel-air ratio considerably increased with increases in the average fuel-air ratio. The rapid enrichment of cylinder 17 contributed greatly to the large fuel-air-ratio spreads of 0.021, 0.035, and 0.047 at average fuel-air ratios of 0.068, 0.078, and 0.084, respectively.

Changes in the average fuel-air ratio of the engine did not result in any significant changes in the fuel-air-ratio pattern produced by the NACA impinging-jets nozzle bar and safety fuel. The leanest cylinders were 13 and 14 and cylinder 7 was richest throughout the range of average fuel-air ratios. The spread increased with an increase in fuel-air ratio, the values being 0.026 and 0.035 at average fuel-air ratios of 0.071 and 0.078, respectively.

For both the standard nozzle bar and the NACA impinging-jets nozzle bar the lower limit of the average fuel-air ratio was restricted to a value of about 0.068 because unstable engine operation resulted from the poor mixture distribution below this value. The increase in the fuel-air ratio spread with an increase in the average fuel-air ratio apparently resulted from less complete fuel vaporization at high fuel flows, where the irregularities of distribution caused by the concentration of fuel droplets were increased.

The results indicated that variations in the mixture distribution of safety fuel resulting from changes in the average fuel-air ratio were insignificant when the NACA injection impeller was used. Use of the NACA injection impeller and safety fuel resulted in slightly less change in spread than did the standard nozzle-bar

injection of gasoline. For all methods of injecting safety fuel and for the standard method of injecting gasoline, the fuel-air-ratio spread tended to increase as the average fuel-air ratio increased.

Effect of Combustion-Air Temperature on Mixture Distribution

The effect of combustion-air temperature on the mixture distribution at 1200 brake horsepower for standard gasoline injection and three methods of safety-fuel injection are shown in figure 10. The mixture distribution of the standard engine for combustion-air temperatures of 65°, 100°, and 126° F are shown in figure 10(a). The general shape of the pattern did not change greatly with a change in the combustion-air temperature but the spread increased from 0.016 at 65° F to 0.021 at 126° F. Usually an increase in combustion-air temperature would be expected to reduce the fuel-air-ratio spread because of the greater vaporization of the fuel resulting from the higher air temperatures. The fuel-air-ratio spread may have increased with an increase in the combustion-air temperature because of the larger throttle opening required when operating at the higher air temperatures. The effects of throttle setting, when using highly volatile gasoline, apparently influence the mixture distribution to a greater extent than does combustion-air temperature.

When safety fuel was injected by the NACA injection impeller, the distribution pattern changed slightly with changes in combustion-air temperature (fig. 10(b)). At 67° F the right half of the engine was somewhat leaner than the left half but as the combustion-air temperature increased this difference decreased until at a temperature of 127° F there was no definite rich or lean portion of the engine. The fuel-air-ratio spread decreased with an increase in combustion-air temperature, the spread being 0.021, 0.013, and 0.012 at temperatures of 67°, 100°, and 127° F, respectively.

For standard nozzle-bar injection of safety fuel, the mixture-distribution pattern changed considerably with changes in the combustion-air temperature. At a temperature of 76° F, cylinders 1, 7, 8, 9, and 17 were about 0.010 richer and cylinders 4, 5, and 12 through 16 were about 0.010 leaner than the average fuel-air ratio for this run. At a combustion-air temperature of 100° F, the pattern was similar to that for 76° F but the deviation of the richest and the leanest cylinders from the average fuel-air ratio was less. For a combustion-air temperature of 139° F the pattern

had leveled off considerably. The variation of the fuel-air ratio among cylinders was much less than it was at lower combustion-air temperatures. The fuel-air ratio spread was 0.027, 0.021, and 0.014 for combustion-air temperatures of 76°, 100°, and 139° F, respectively.

The combustion-air temperature had a marked effect on mixture distribution when safety fuel was injected by the NACA impinging-jets nozzle bar as shown in figure 10(d). At a combustion-air temperature of 77° F cylinder 7 was comparatively rich whereas cylinders 14, 16, and 17 were extremely lean. As the combustion-air temperature was increased to 100° F, the deviation of the rich and the lean cylinders from the average fuel-air ratio was less but the distribution was still poor. At a combustion-air temperature of 135° F, the distribution was improved considerably with most cylinders operating at fuel-air ratios very close to the average fuel-air ratio. Cylinders 13 and 14 were operating relatively lean. The fuel-air-ratio spread decreased as the combustion-air temperature increased; the values of the spread were 0.037, 0.026, and 0.016 at temperatures of 77°, 100°, and 135° F, respectively. For both standard nozzle-bar and NACA impinging-jets nozzle-bar injection of safety fuel, the lowest combustion-air temperature at which the engine would operate satisfactorily was about 75° F. Below this temperature, the mixture distribution apparently became so poor that unsteady engine operation resulted.

Each method of safety-fuel injection showed an improvement in mixture distribution as the combustion-air temperature increased. This improvement apparently resulted from more complete vaporization of the fuel at the higher combustion-air temperatures. Over the range of combustion-air temperatures investigated, the best mixture distribution of safety fuel was obtained with the injection impeller. The injection impeller produced the least spread in fuel-air ratio and the least change in spread for a given change in the combustion-air temperature. At a combustion-air temperature of about 66° F, the fuel-air ratio spread for the combination of safety fuel and the NACA injection impeller produced a spread of about 31 percent greater than that for the standard method of injecting gasoline. At the higher temperatures, however, the injection impeller and safety fuel resulted in fuel-air-ratio spreads that averaged 33 percent lower than those of the standard engine. Although both the standard nozzle bar and the NACA impinging-jets nozzle bar produced satisfactory distribution of safety fuel at combustion-air temperatures of about 137° F, actual operation of the engine with combustion-air above approximately 100° F is usually undesirable because high combustion-air temperature increases the tendency for the engine to detonate and reduces the weight of charge air introduced into the engine at a given manifold pressure.

A summary of the results of the investigations at standard powers and with varying average fuel-air ratio and combustion-air temperature is presented in table I.

Although the mixture distribution obtained with the NACA injection impeller and safety fuel was better than that obtained with the standard engine, design modifications might further improve the mixture distribution.

Unavailable data show that design modification of the NACA injection impeller, made primarily to improve dispersion of the fuel as it left the fuel-injection passages, did not improve the performance of the engine when gasoline was used. These modifications may offer improvement, however, with safety fuel because the atomization of safety fuel to obtain a higher degree of vaporization is more important than with gasoline.

General Engine Performance

The absolute manifold pressure and combustion-air flow required for a given engine power are shown for the three methods of injecting safety fuel and for the standard engine and gasoline in figure 11. Between 1200 and 1600 brake horsepower, the required absolute manifold pressure and combustion-air flow ranged from 1.5 to 6 percent more for the three methods of safety-fuel injection than for the standard method of injecting gasoline. In general, safety-fuel injection with the NACA injection impeller required the least manifold pressure and air flow of the three methods of injection. As the limiting power was approached, the differences in air flow and manifold pressure required for the safety-fuel injection methods and the standard engine became greater. With the standard engine, full rated power of 2000 brake horsepower at 2400 rpm and atmospheric deck pressure was obtained. With the NACA injection impeller and safety fuel, 1890 brake horsepower was obtained under these same conditions and with the standard nozzle bar and the NACA impinging-jets nozzle bar, 1670 and 1790 brake horsepower, respectively, were obtained. A portion of the power limitation probably resulted from the poor mixture distribution at the higher powers. The nonuniformity of the mixture distribution may also have adversely affected the volumetric efficiency of certain cylinders. Because the safety fuel did not vaporize as completely as gasoline, higher combustion-air temperatures downstream of the carburetor probably resulted when safety fuel was used, thus decreasing the weight of charge air introduced into the cylinders at a given manifold pressure.

The brake specific fuel consumption for various over-all fuel-air ratios at 1200 brake horsepower is shown in figure 12 for the three methods of injecting safety fuel and for the standard engine. The brake specific fuel consumption for each method of safety-fuel injection was the same throughout the range of fuel-air ratios. The standard engine followed the same general curve but averaged about 6 percent lower than the safety-fuel injection.

Idling and Starting

Starting attempts were made with safety fuel A for each method of fuel injection and with safety fuel B for only the NACA injection impeller. Starting was attempted about 10 minutes after stopping the engine following a normal cruising power run. The rear-spark-plug-gasket temperatures were approximately 200° F when starting was attempted. Starting was also attempted at temperatures of 50° to 60° F after the engine had been standing overnight. Starting the engine was impossible with safety fuel A under both starting conditions with any of the three injection methods but idling as low as 800 rpm was satisfactory with all three methods. When safety fuel B was used with the NACA injection impeller, the engine started satisfactorily when warm but would not start when cold. Idling with this fuel was also satisfactory. Reference 2 shows that when a single-cylinder engine is primed with gasoline and then switched to safety fuel, satisfactory starting is obtained. This same method might be satisfactory for a multi-cylinder engine. Reference 2 also presents a method of using propane for starting a multicylinder engine that is to be run on safety fuel.

SUMMARY OF RESULTS

The results of the investigation to determine if safety fuel could be successfully used in a double-row, radial aircraft engine with a simple means of injection in place of direct-cylinder injection are summarized as follows:

1. Satisfactory mixture distribution of safety fuel resulted when the NACA injection impeller was employed. Throughout the range of engine powers, average fuel-air ratios, and combustion-air temperatures, the NACA injection impeller produced better mixture distribution of safety fuel than did the standard method of injecting gasoline. However, when either the NACA impinging-jets nozzle bar or the standard nozzle bar was used for safety-fuel injection, the

mixture distribution was unsatisfactory. The mixture distribution obtained with safety fuel injected by the NACA injection impeller was less affected by changes in engine power, average fuel-air ratio, and combustion-air temperature than was that obtained with the other methods of injection.

2. The poor mixture distribution that resulted when safety fuel was injected by the NACA impinging-jets nozzle bar or the standard nozzle bar considerably reduced the maximum power output of the engine. It also restricted the lower limits of the average fuel-air ratio and the combustion-air temperature at which the engine would operate steadily.

3. Between 1200 and 1600 brake horsepower the required absolute manifold pressure and combustion-air flow ranged from 1.5 to 6.0 percent more for the three methods of safety-fuel injection than for the standard method of injecting gasoline. Safety-fuel injection with the NACA injection impeller required the least manifold pressure and air flow of the three methods of injection.

4. The brake specific fuel consumption at 1200 brake horsepower for all methods of safety-fuel injection was about 6 percent higher than for standard injection of gasoline.

5. Idling characteristics of the engine when using safety fuel were satisfactory but starting with the engine either warm or cold was impossible when safety fuel A (flash point, 122° F) was used. Starting was accomplished, however, using safety fuel B (flash point, 99° F) when the engine was warm.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 9, 1947.

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TABLE I

FUEL-AIR RATIO AND TEMPERATURE SPREADS FOR VARIOUS ENGINE CONDITIONS

Power (bhp)	Engine speed (rpm)	Approximate average fuel-air ratio	Approximate combustion-air temperature (°F)	Standard engine (Gasoline)			NACA injection impeller (Safety fuel)			NACA impinging-jets nozzle bar (Safety fuel)			Standard nozzle bar (Safety fuel)		
				Spread			Spread			Spread			Spread		
				Fuel-air ratio	Rear-spark-plug-gasket temperature (°F)	Exhaust-valve-seat temperature (°F)	Fuel-air ratio	Rear-spark-plug-gasket temperature (°F)	Exhaust-valve-seat temperature (°F)	Fuel-air ratio	Rear-spark-plug-gasket temperature (°F)	Exhaust-valve-seat temperature (°F)	Fuel-air ratio	Rear-spark-plug-gasket temperature (°F)	Exhaust-valve-seat temperature (°F)
1200	2000	0.070	100	0.017	90	190	0.013	75	132	0.026	77	124	0.021	69	102
1400	2100	.082		.024	108	196	.013	81	126	.040	137	224	(a)	(a)	(a)
1600	2200	.087		.021	113	194	.018	105	150	.037	167	250	.052	150	221
1800	2300	.091		.023	119	192	.016	91	140	(a)	(a)	(a)	(a)	(a)	(a)
1200	2000	0.082	100	0.022	(a)	(a)	0.017	(a)	(a)	0.035	(a)	(a)	0.047	(a)	(a)
		.070		.017			.013			.026			.035		
		.065		.018			.014			(a)			.021		
1200	2000	0.088	132	0.021	(a)	(a)	0.012	(a)	(a)	0.014	(a)	(a)	0.016	(a)	(a)
			100	.017			.013			.021			.026		
			70	.016			.021			.027			.037		

^aNo data taken.NATIONAL ADVISORY
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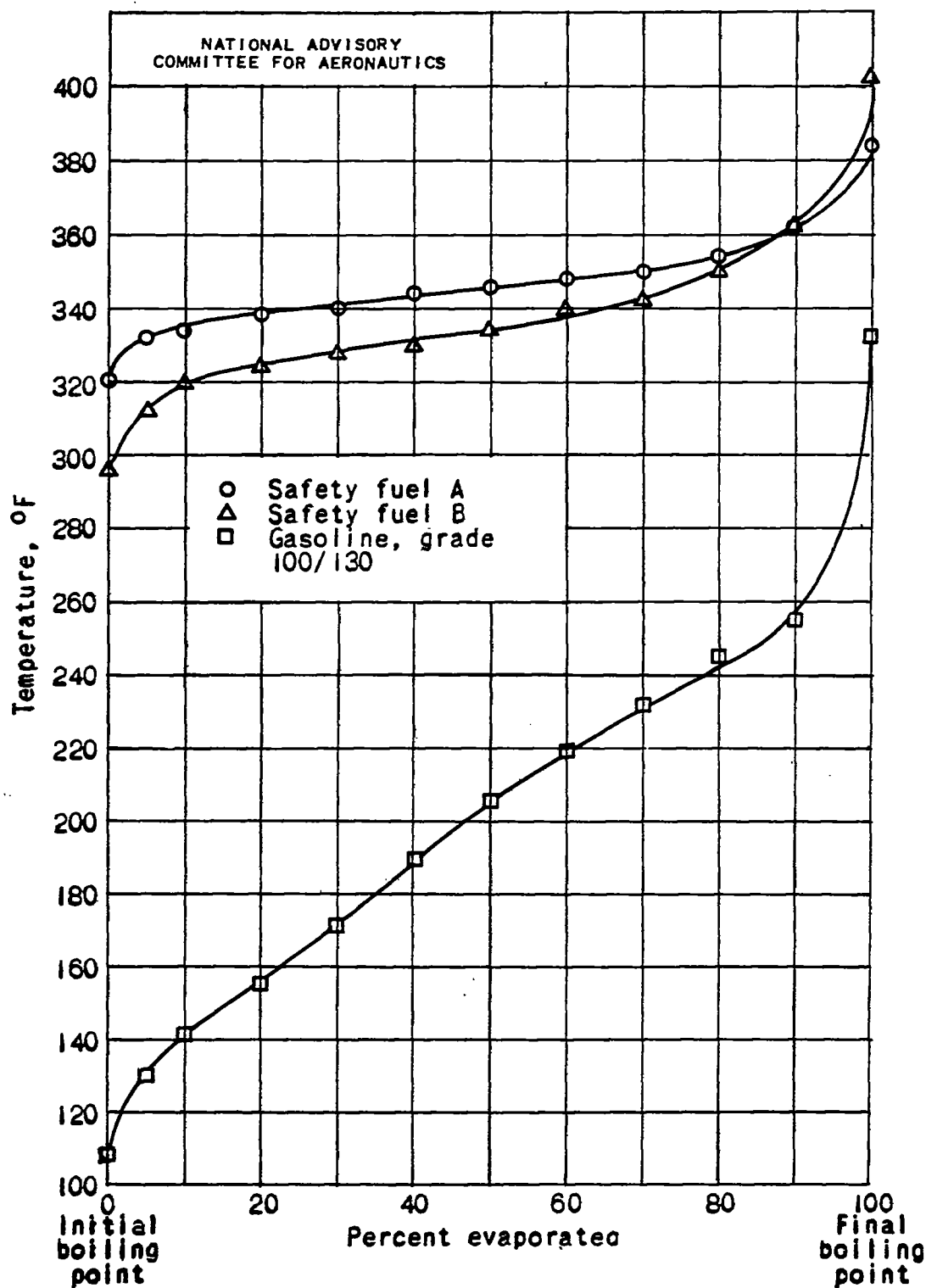


Figure 1. - Distillation curves of gasoline, safety fuel A, and safety fuel B.

Fig. 2

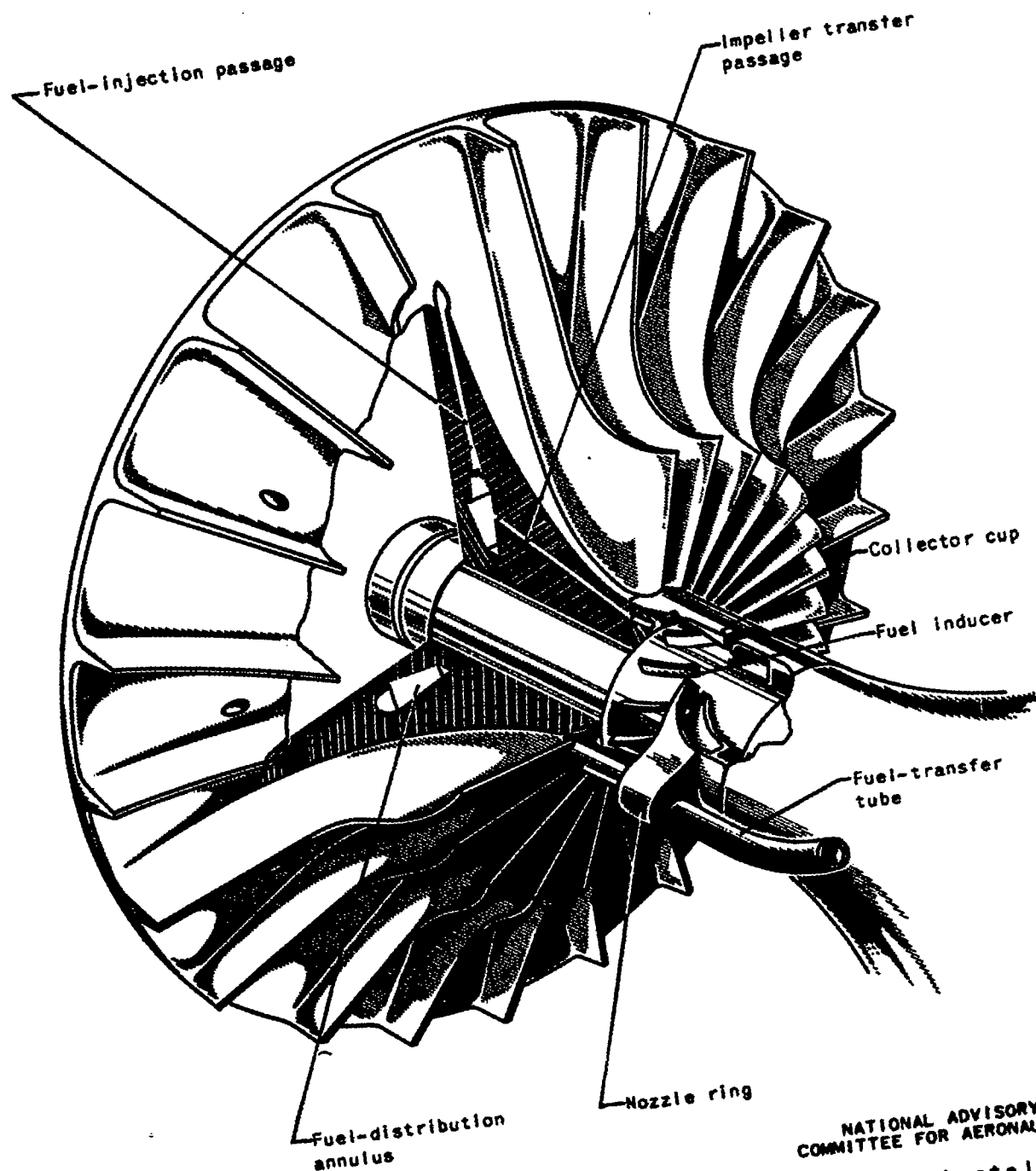
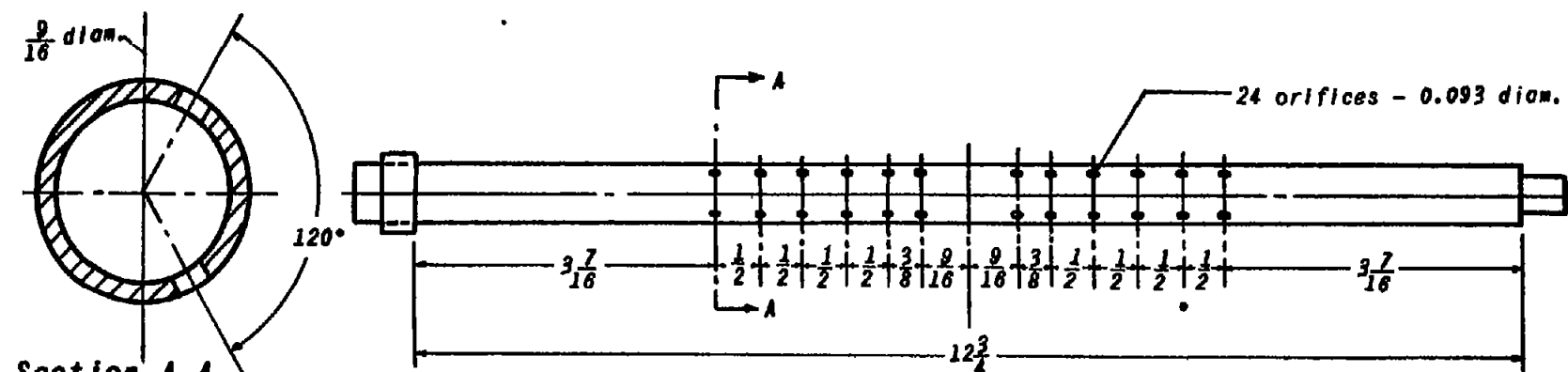


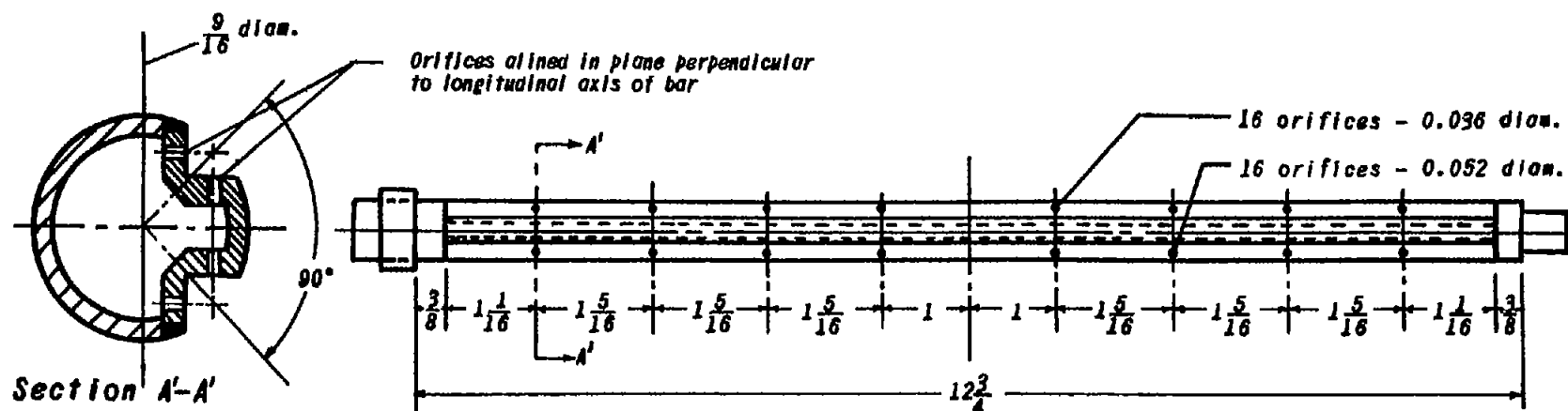
Figure 2. - NACA injection impeller designed for installation on double-row radial aircraft engine.

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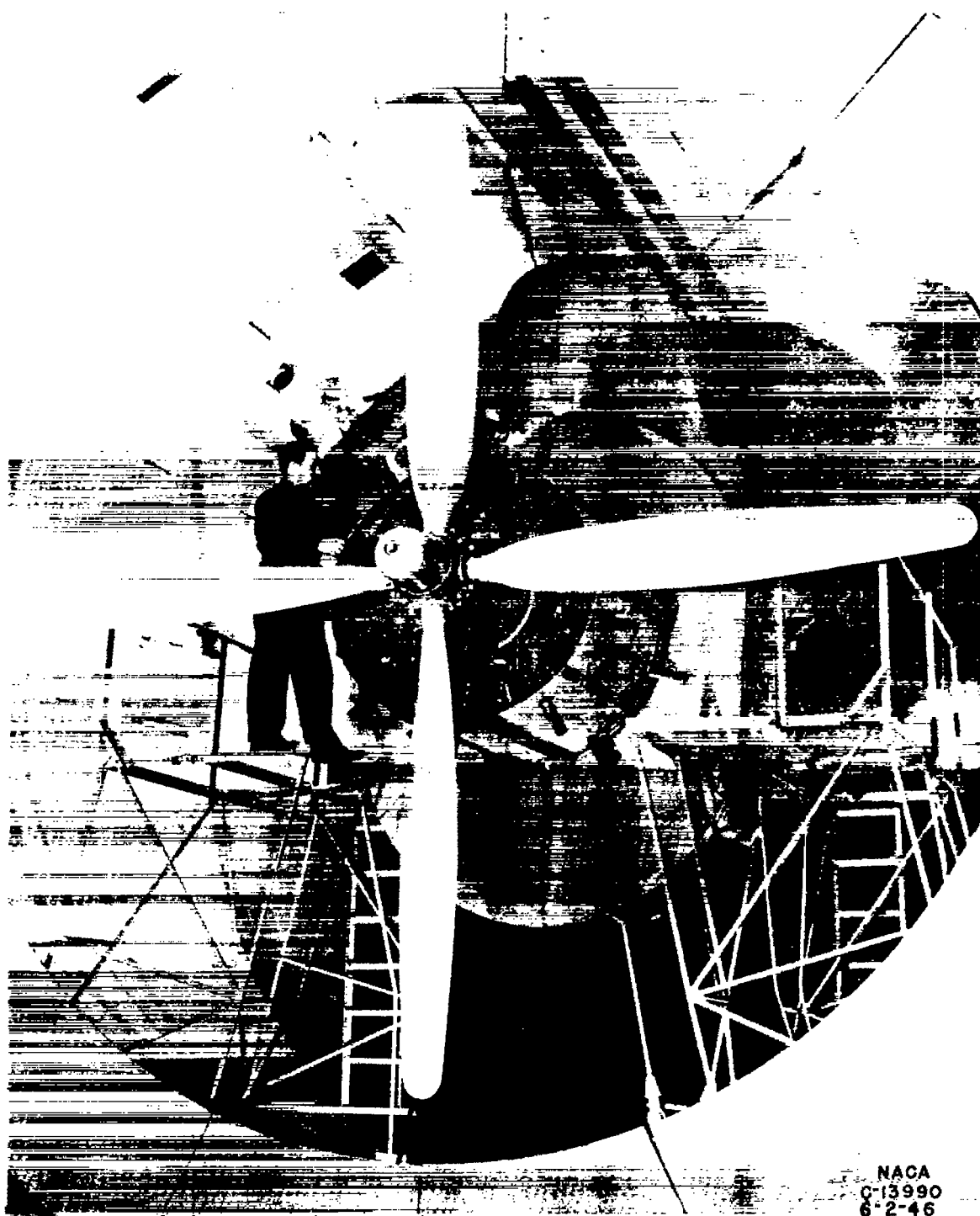


(a) Standard nozzle bar.



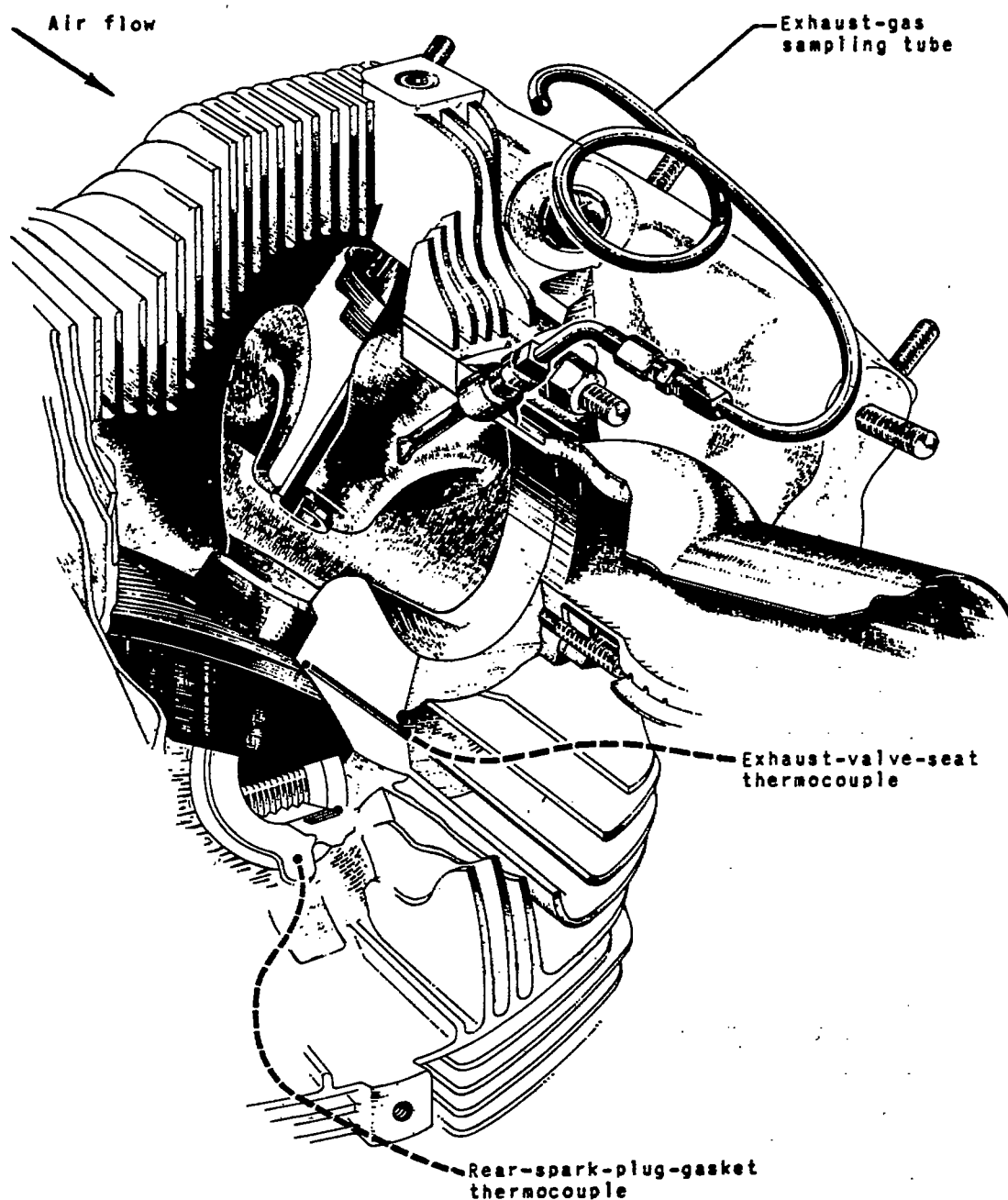
(b) NACA impinging-jets nozzle bar.

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(All dimensions in inches.)



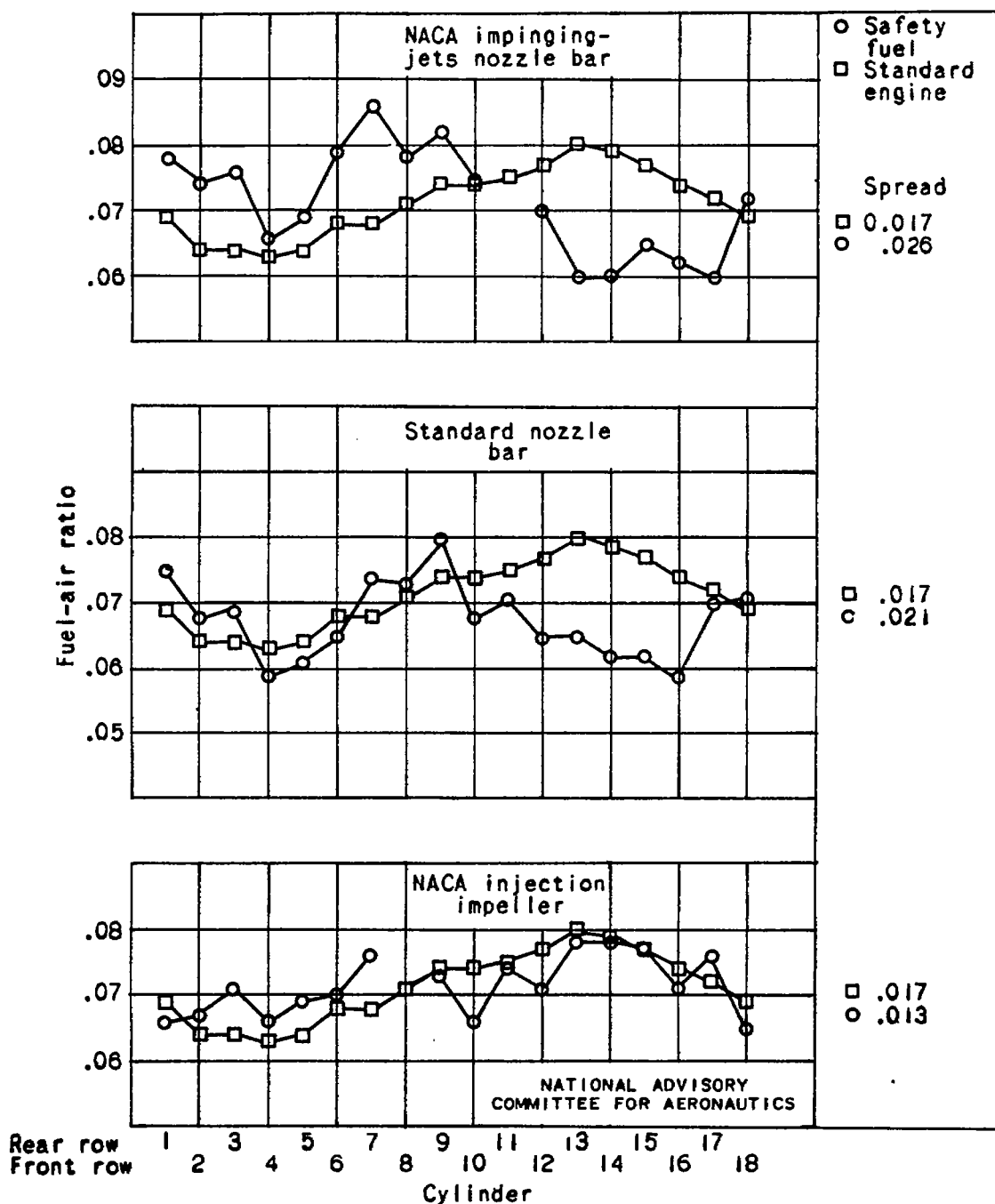
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Figure 4. - Test-cell installation of double-row radial aircraft engine.



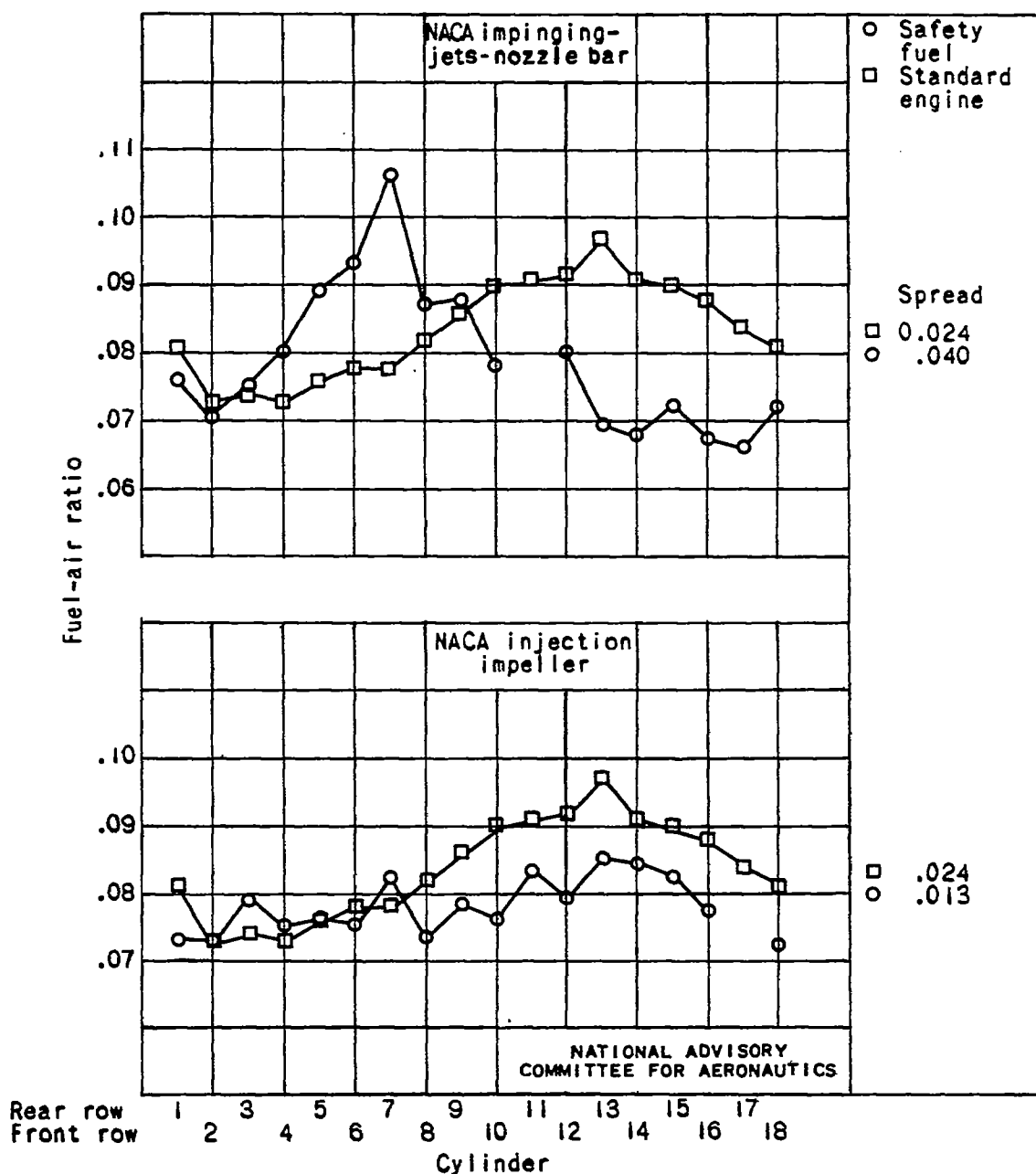
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Figure 5. - Location of thermocouples and exhaust-gas sampling tube.



(a) Brake horsepower, 1200; engine speed, 2000 rpm; approximate average fuel-air ratio, 0.070.

Figure 6. - Mixture distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

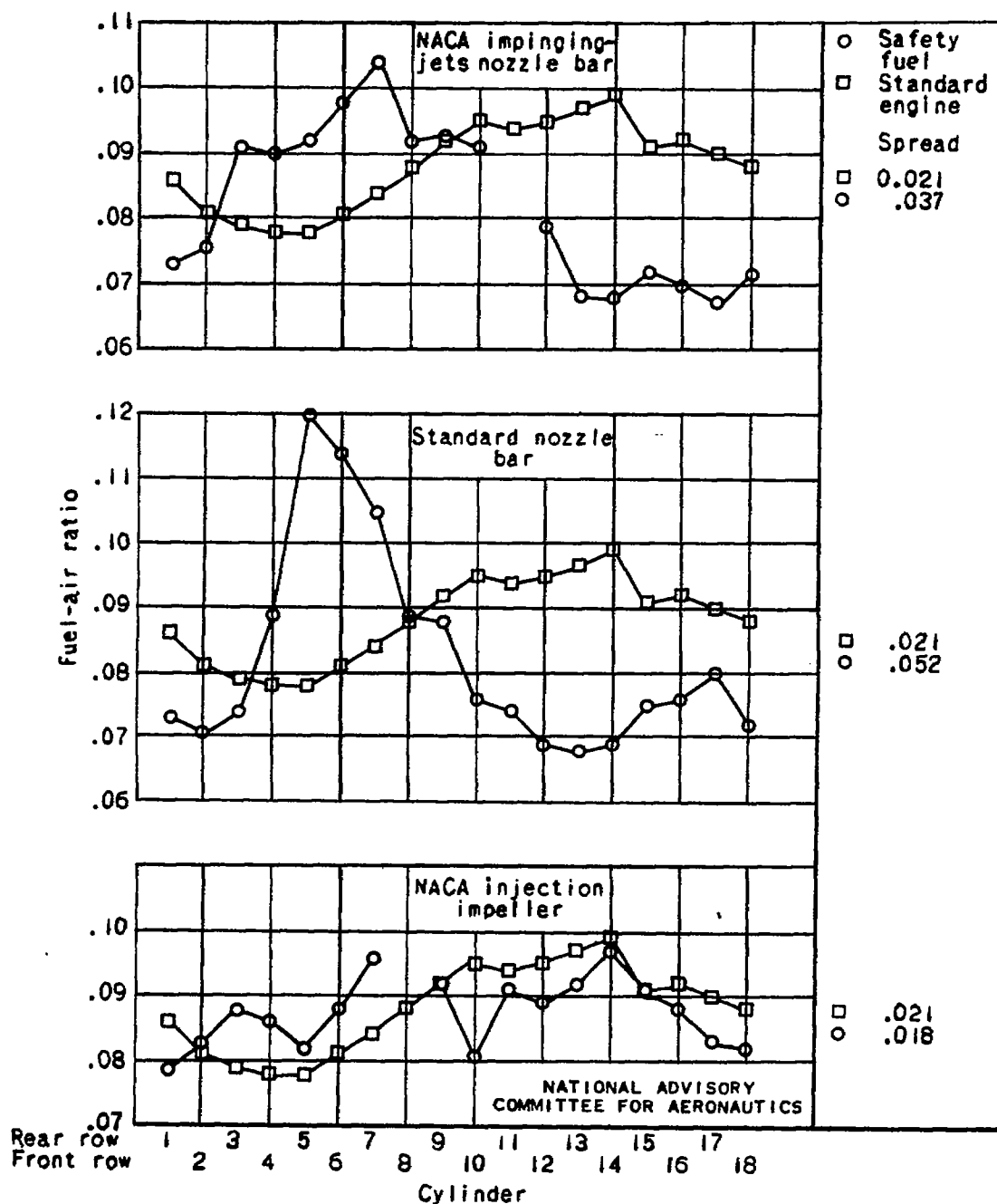


(b) Brake horsepower, 1400; engine speed, 2100 rpm; approximate average fuel-air ratio, 0.082.

Figure 6. - Continued. Mixture distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

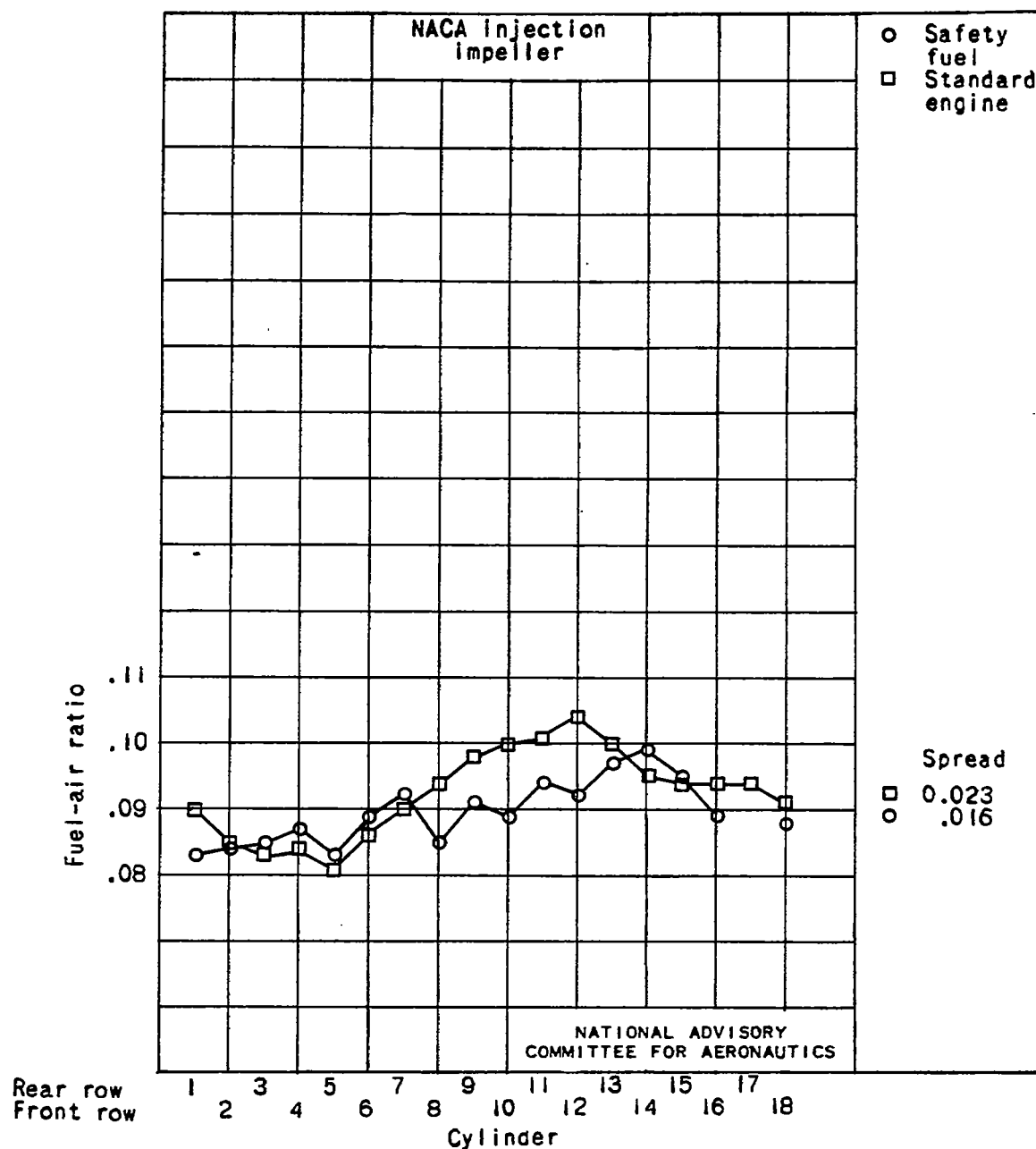
Fig. 6c

NACA TN No. 1413



(c) Brake horsepower, 1600; engine speed, 2200 rpm; approximate average fuel-air ratio, 0.087.

Figure 6. - Continued. Mixture distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

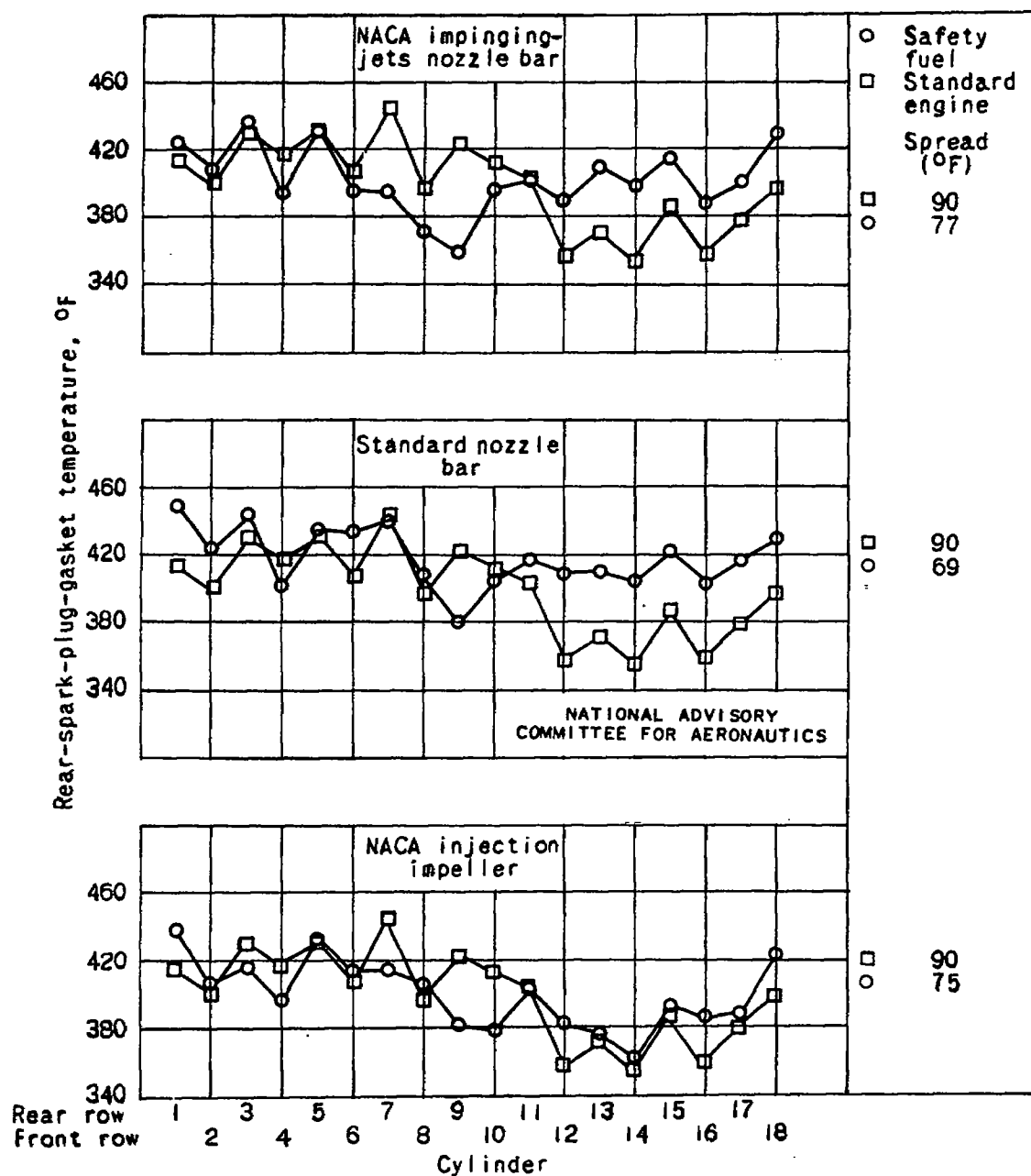


(d) Brake horsepower, 1800; engine speed, 2300 rpm; approximate average fuel-air ratio, 0.091.

Figure 6. - Concluded. Mixture distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

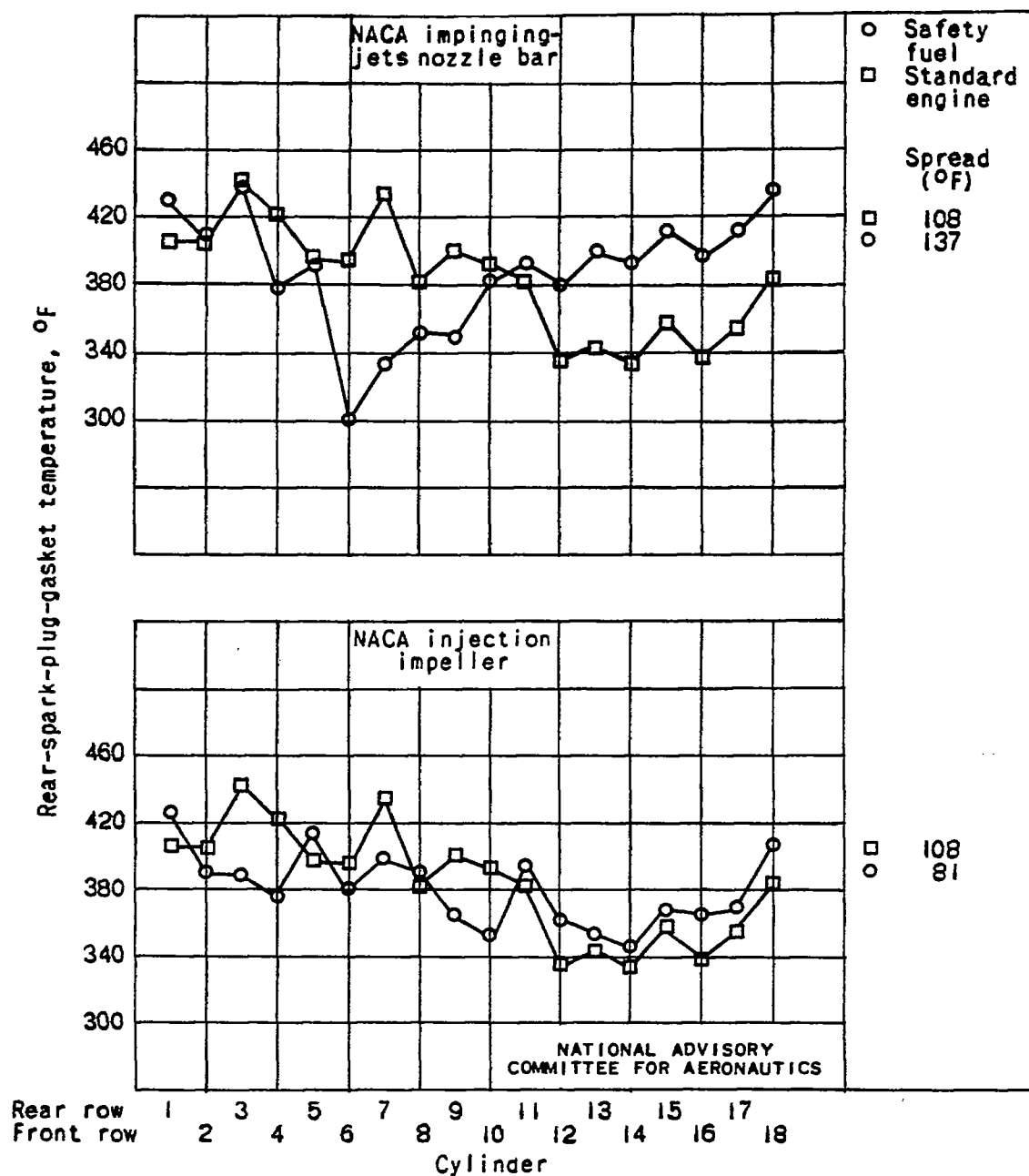
Fig. 7a

NACA TN No. 1413



(a) Brake horsepower, 1200; engine speed, 2000 rpm; approximate average fuel-air ratio, 0.070.

Figure 7. - Rear-spark-plug-gasket temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

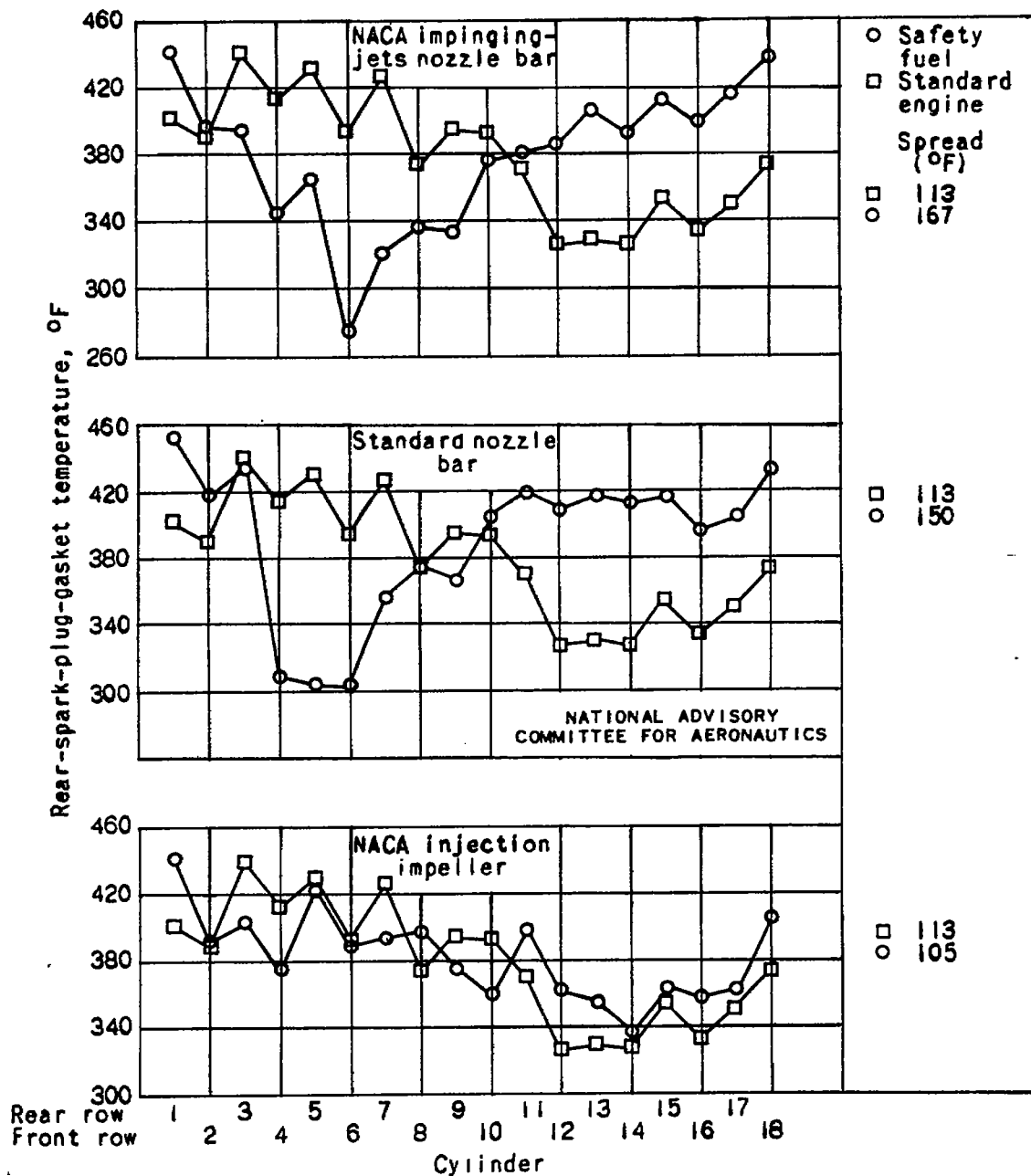


(b). Brake horsepower, 1400; engine speed, 2100 rpm; approximate average fuel-air ratio, 0.082.

Figure 7. - Continued. Rear-spark-plug-gasket temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

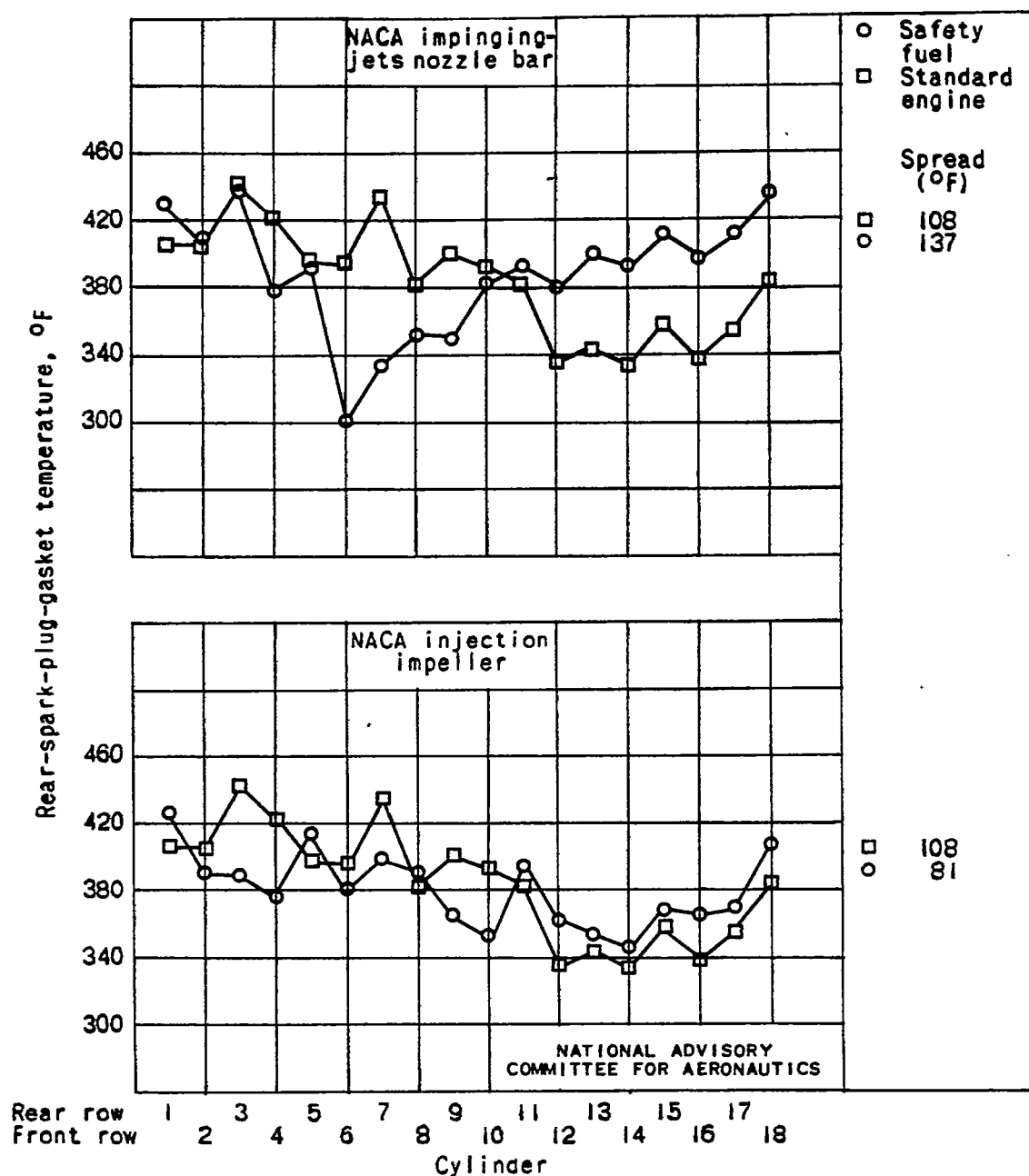
Fig. 7c

NACA TN No. 1413



(c) Brake horsepower, 1600; engine speed, 2200 rpm; approximate average fuel-air ratio, 0.087.

Figure 7. - Continued. Rear-spark-plug-gasket temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

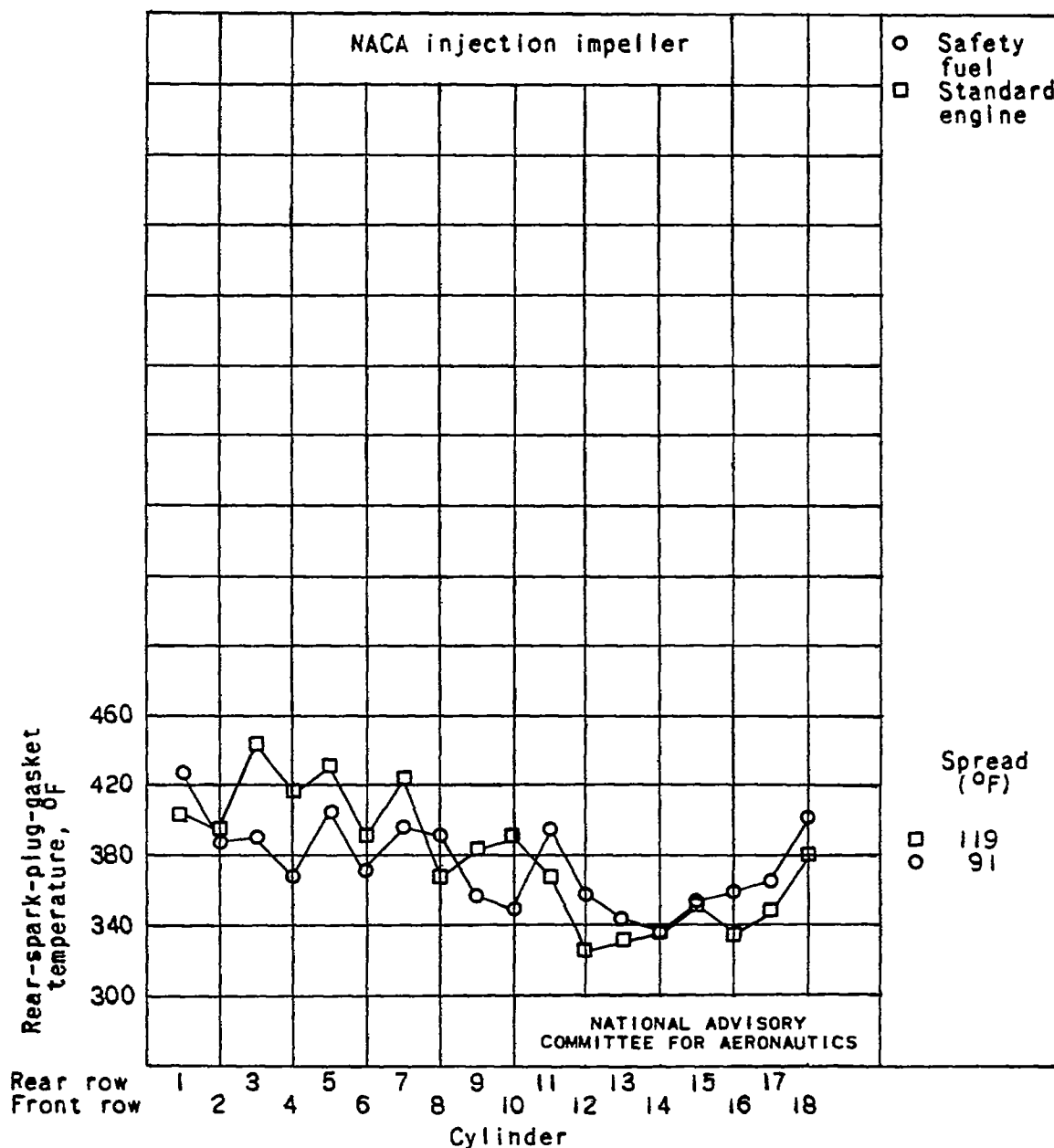


(b) Brake horsepower, 1400; engine speed, 2100 rpm; approximate average fuel-air ratio, 0.082.

Figure 7. - Continued. Rear-spark-plug-gasket temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.



Figure 7. - Continued. Rear-spark-plug-gasket temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

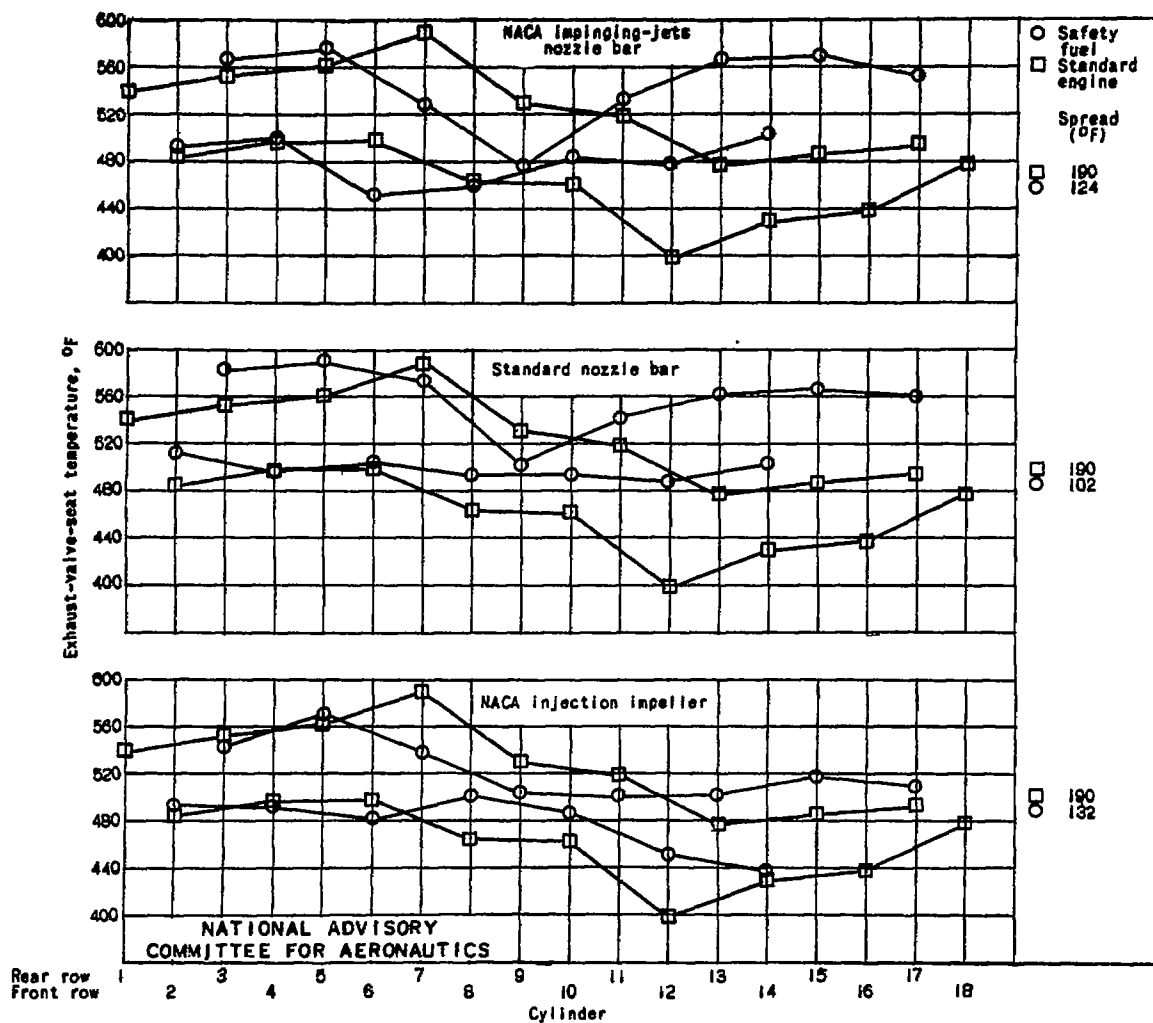


(d) Brake horsepower, 1800; engine speed, 2300 rpm; approximate average fuel-air ratio, 0.091.

Figure 7. - Concluded. Rear-spark-plug-gasket temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

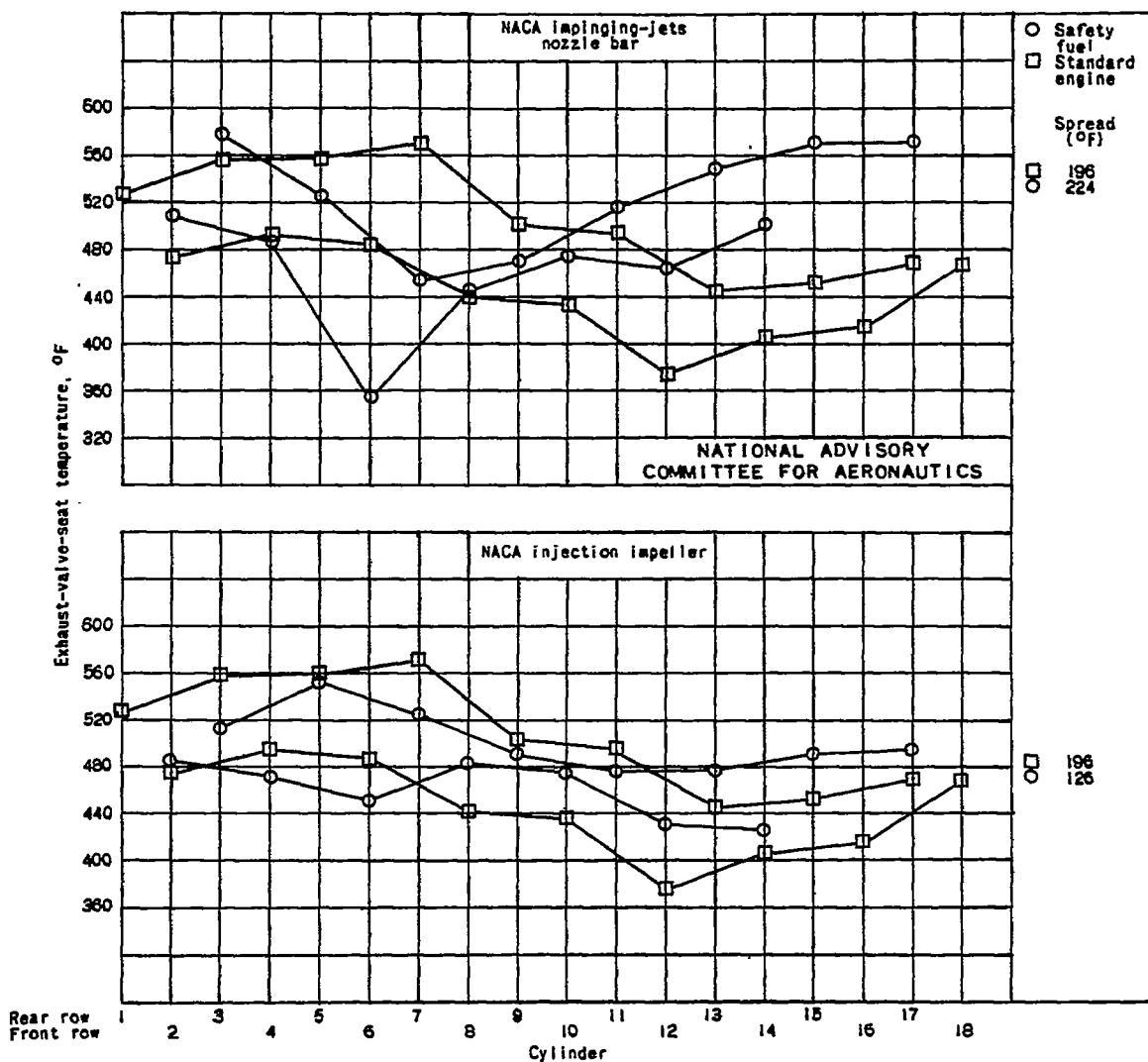
Fig. 8a

NACA TN No. 1413



(a) Brake horsepower, 1200; engine speed, 2000 rpm; approximate average fuel-air ratio, 0.070.

Figure 8. - Exhaust-valve-seat temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 1000° F.

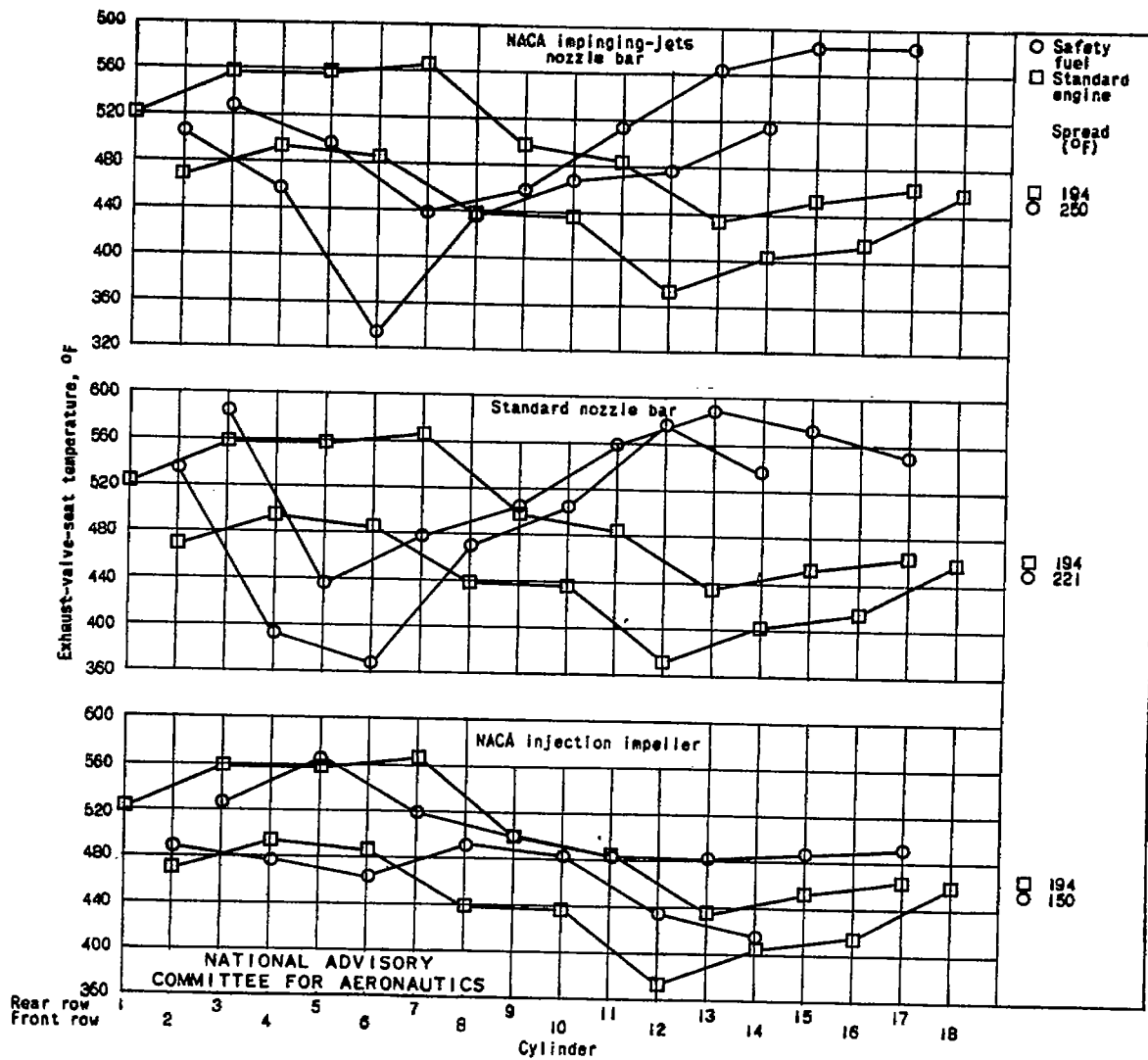


(b) Brake horsepower, 1400; engine speed, 2100 rpm; approximate average fuel-air ratio, 0.082.

Figure 8. - Continued. Exhaust-valve-seat temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

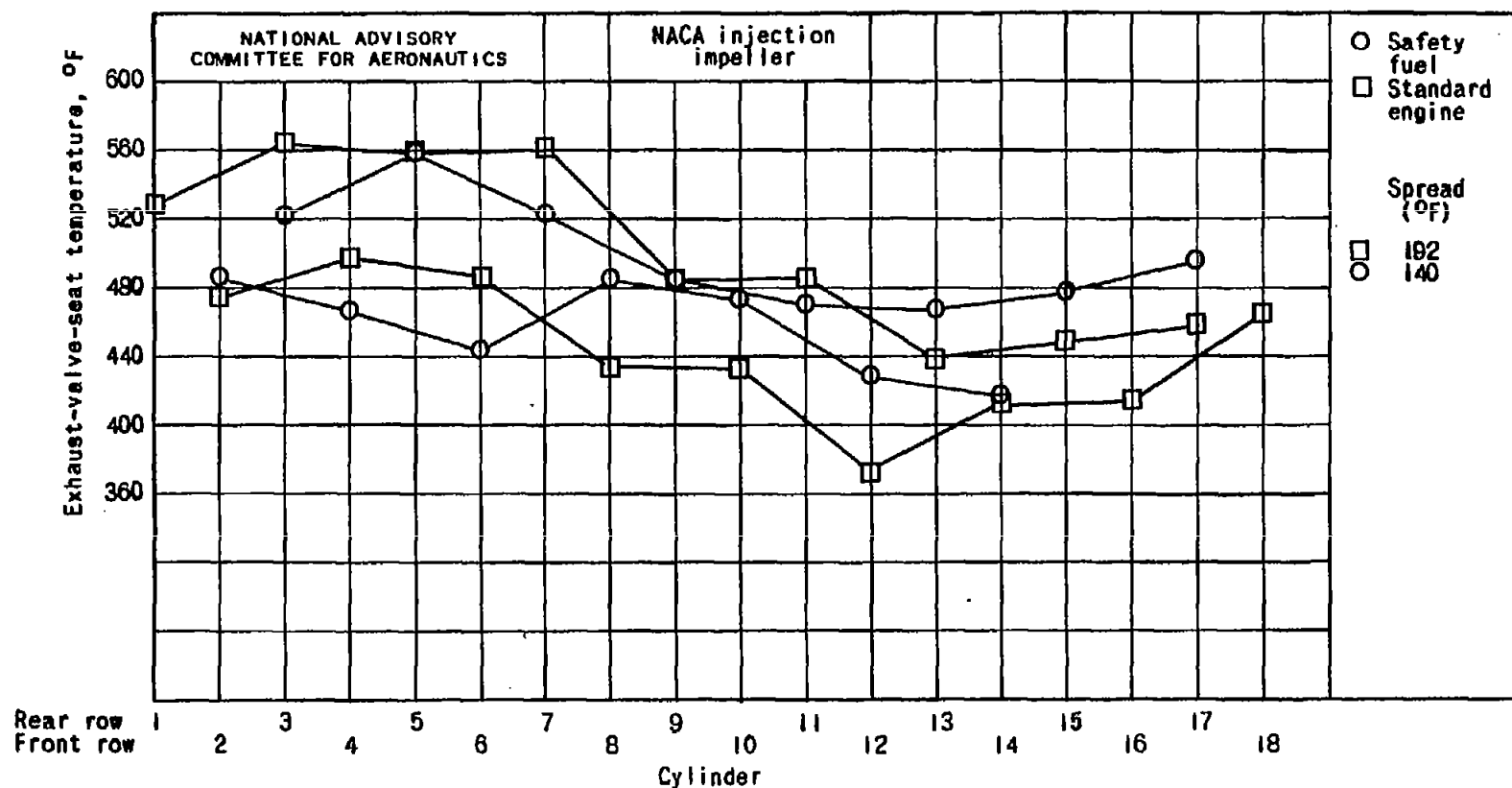
Fig. 8c

NACA TN No. 1413



(c) Brake horsepower, 1600; engine speed, 2200 rpm; approximate average fuel-air ratio, 0.087.

Figure 8. - Continued. Exhaust-valve-seat temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 1000° F.



(d) Brake horsepower, 1800; engine speed, 2300 rpm; approximate average fuel-air ratio, 0.091.

Figure 8. - Concluded. Exhaust-valve-seat temperature distribution obtained at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Combustion-air temperature, 100° F.

Fig. 9

NACA TN No. 1413

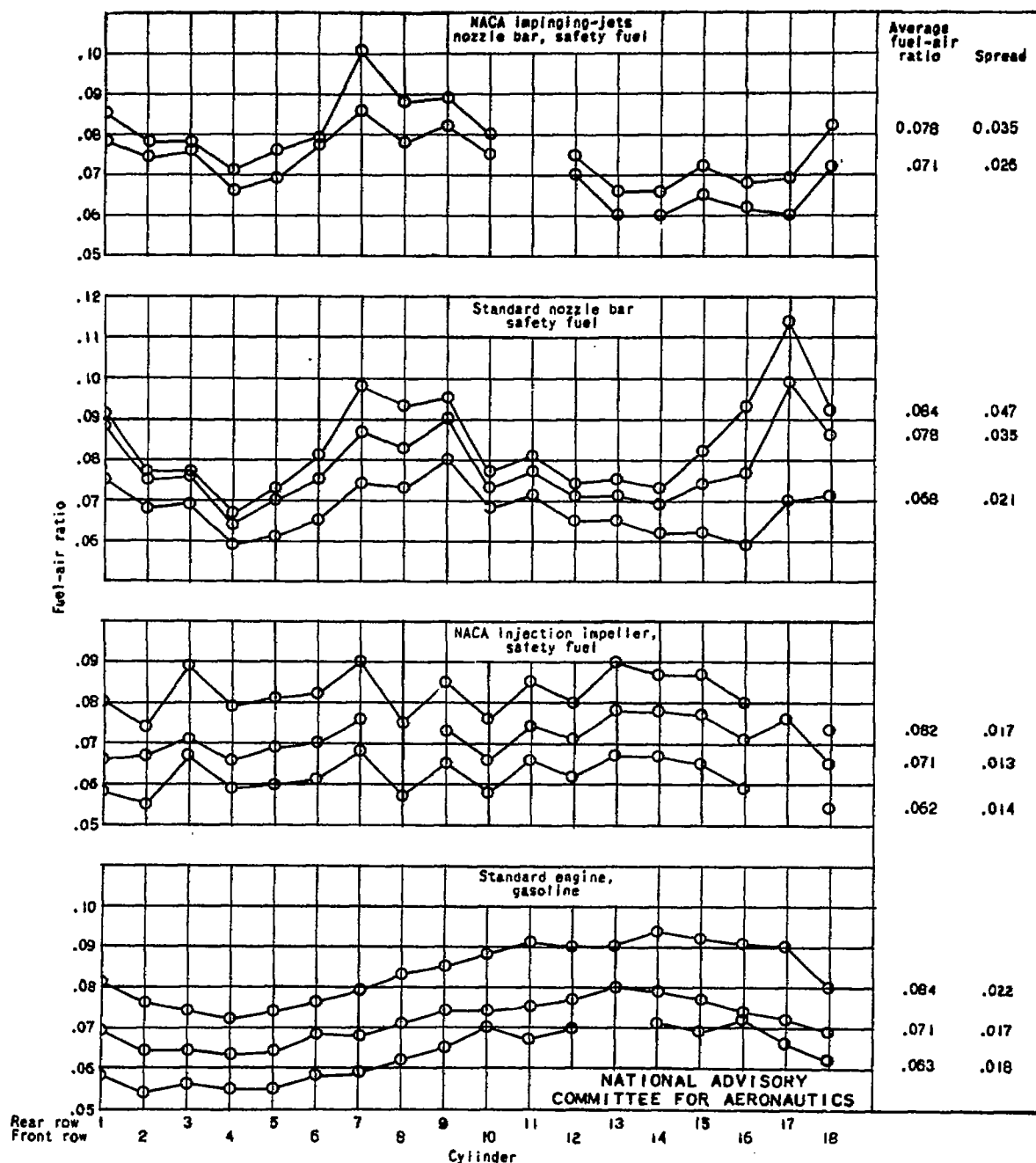
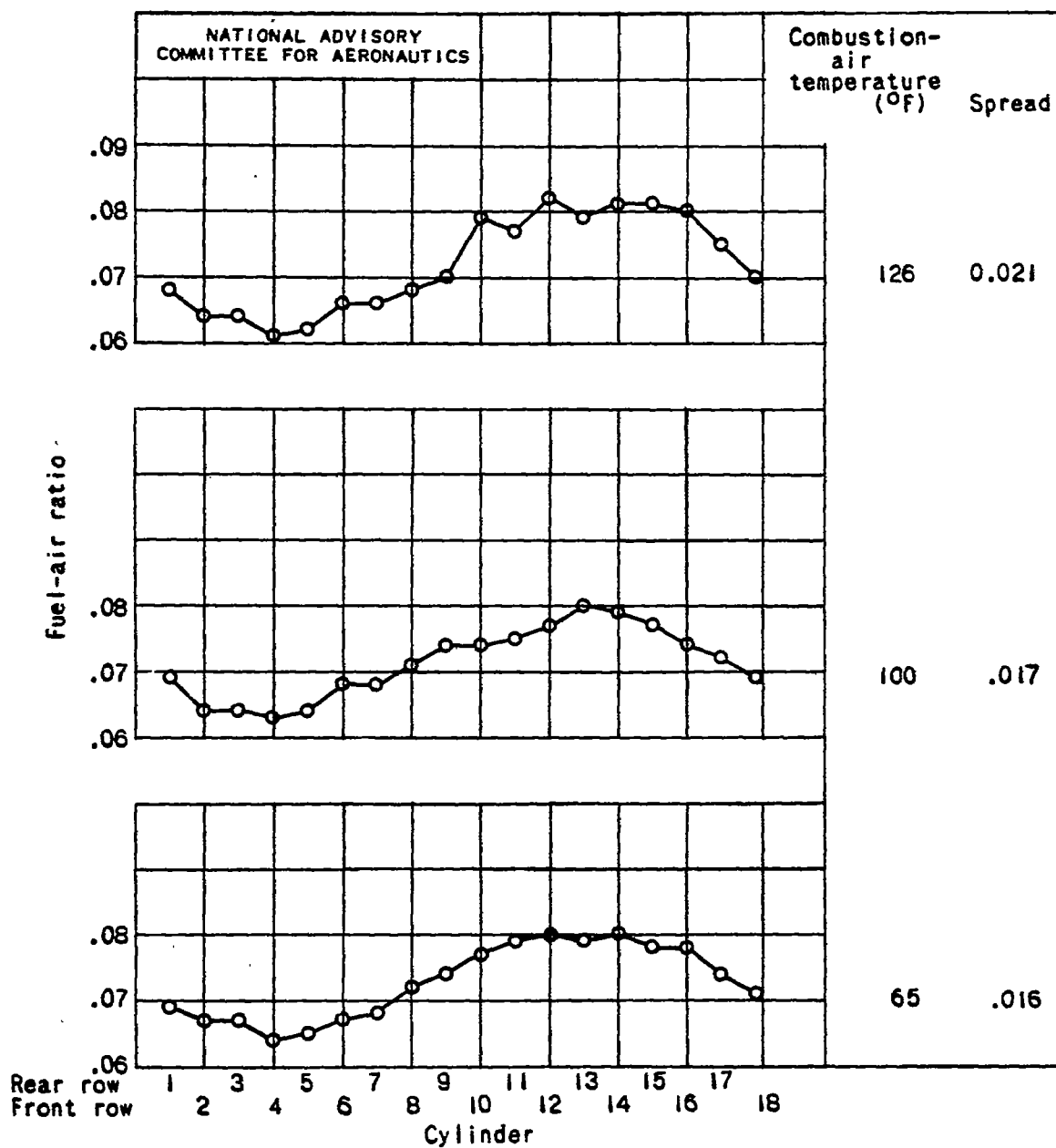


Figure 9. - Mixture distribution obtained at several average fuel-air ratios for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Brake horsepower, 1200; combustion-air temperature, 100° F.

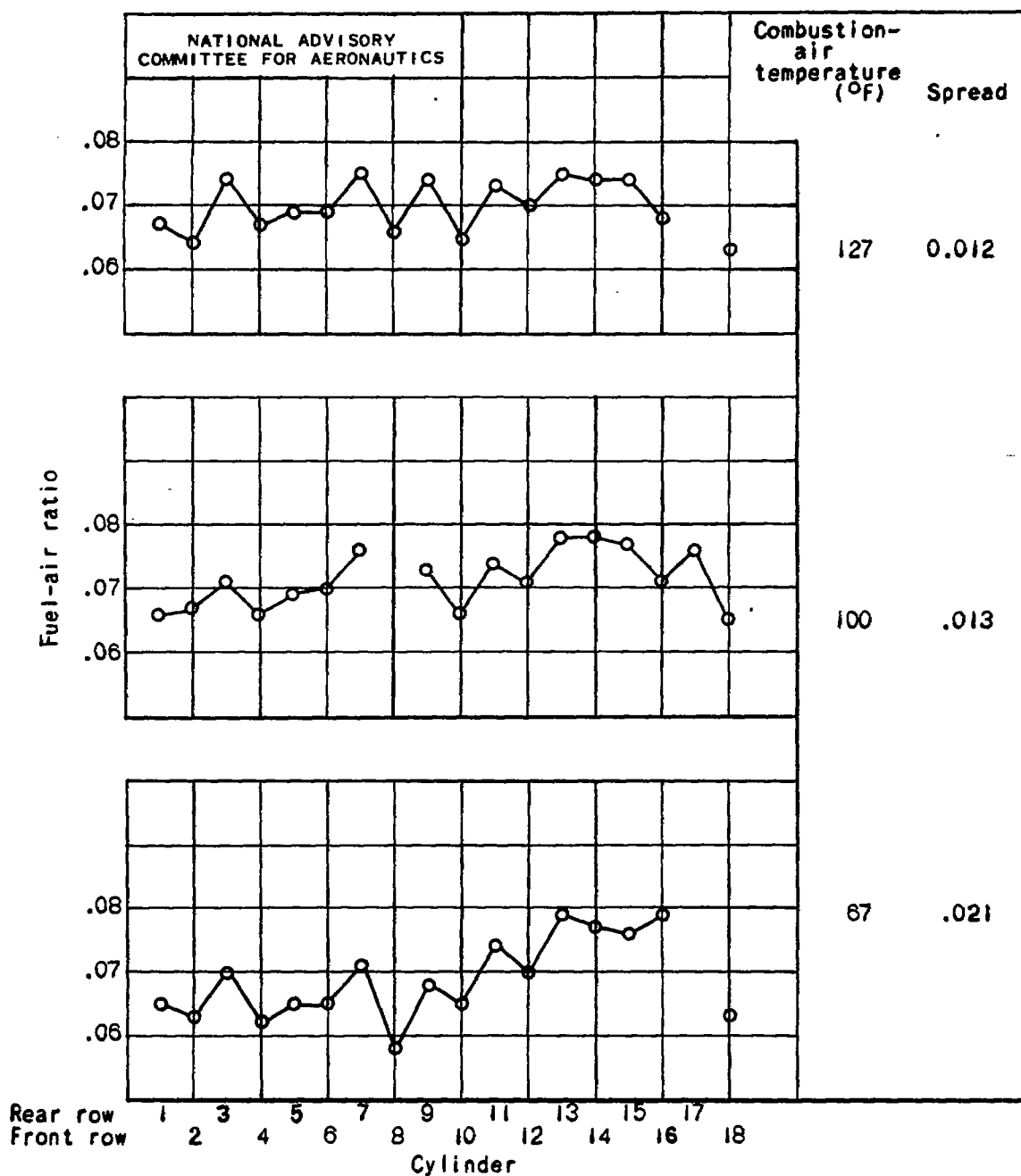


(a) Standard engine, gasoline.

Figure 10. - Mixture distribution obtained at several combustion-air temperatures for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Brake horsepower, 1200; approximate average fuel-air ratio, 0.069.

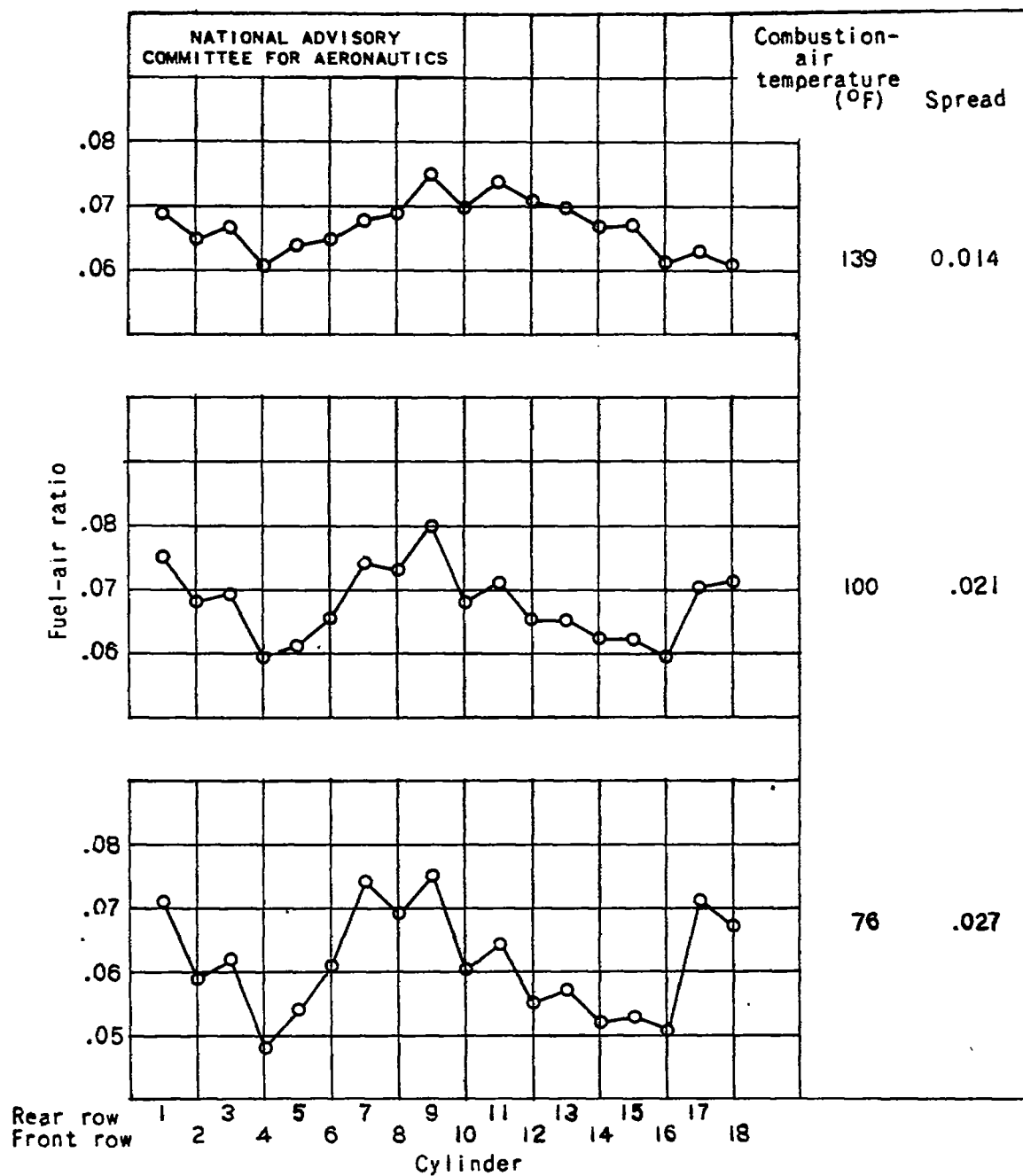
Fig. 10b

NACA TN No. 1413



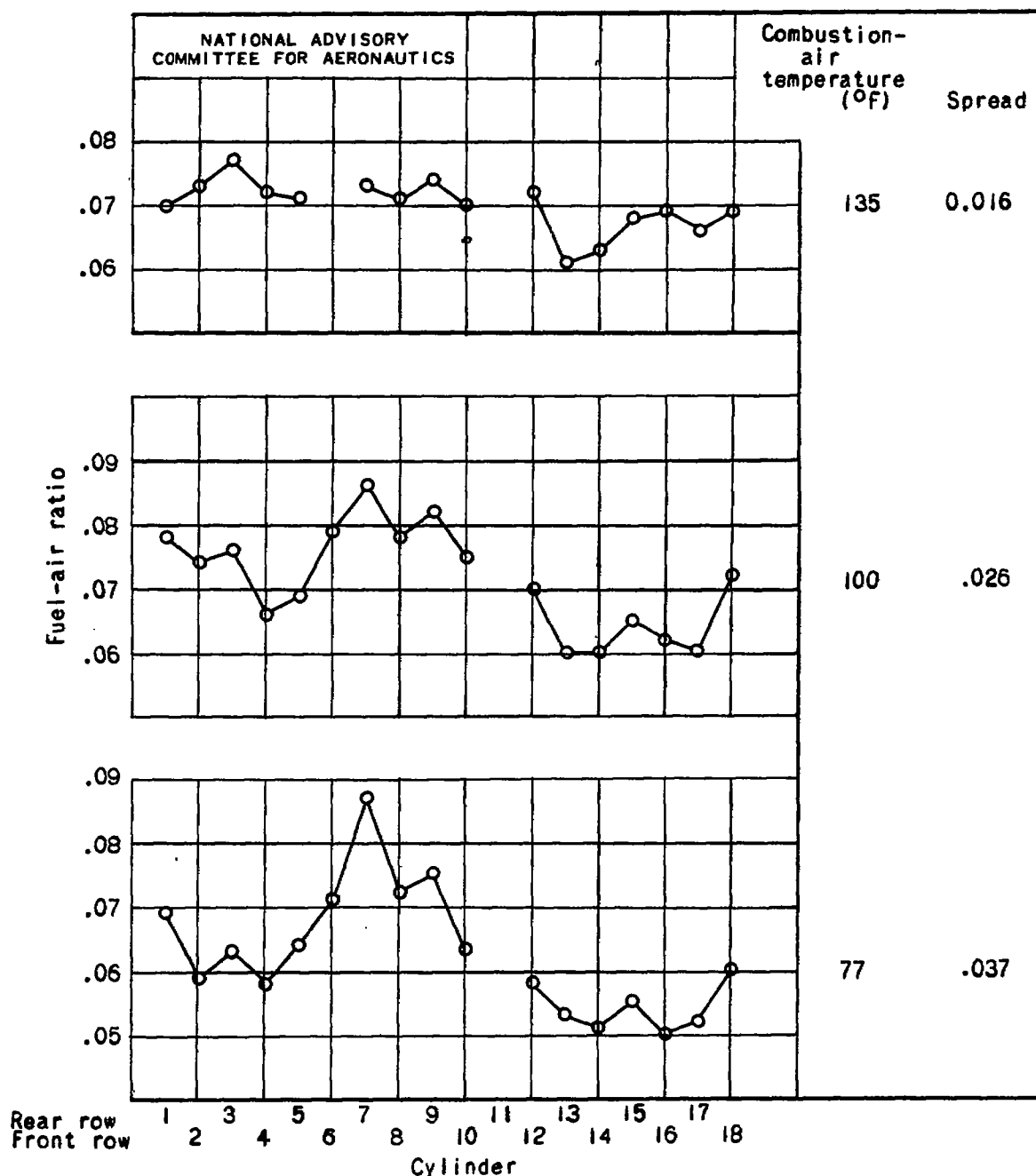
(b) NACA injection impeller, safety fuel.

Figure 10. - Continued. Mixture distribution obtained at several combustion-air temperatures for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Brake horsepower, 1200; approximate average fuel-air ratio, 0.069.



(c) Standard nozzle bar, safety fuel.

Figure 10. - Continued. Mixture distribution obtained at several combustion-air temperatures for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Brake horsepower, 1200; approximate average fuel-air ratio, 0.069.



(d) NACA impinging-jets nozzle bar, safety fuel.

Figure 10. - Concluded. Mixture distribution obtained at several combustion-air temperatures for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar. Brake horsepower, 1200; approximate average fuel-air ratio, 0.069.

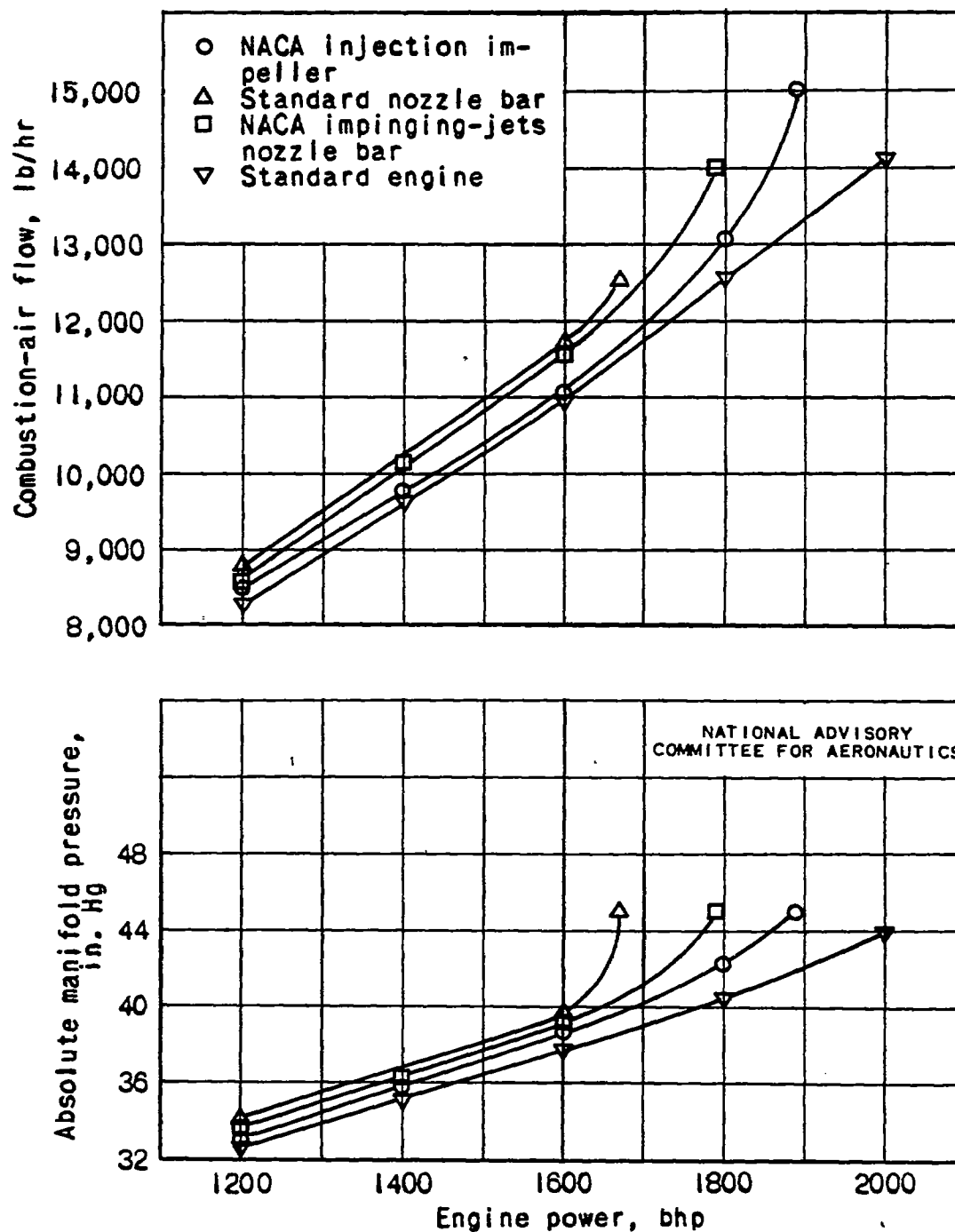


Figure 11. - Engine air flow and manifold pressure required at standard powers for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar.

Fig. 12

NACA TN No. 1413

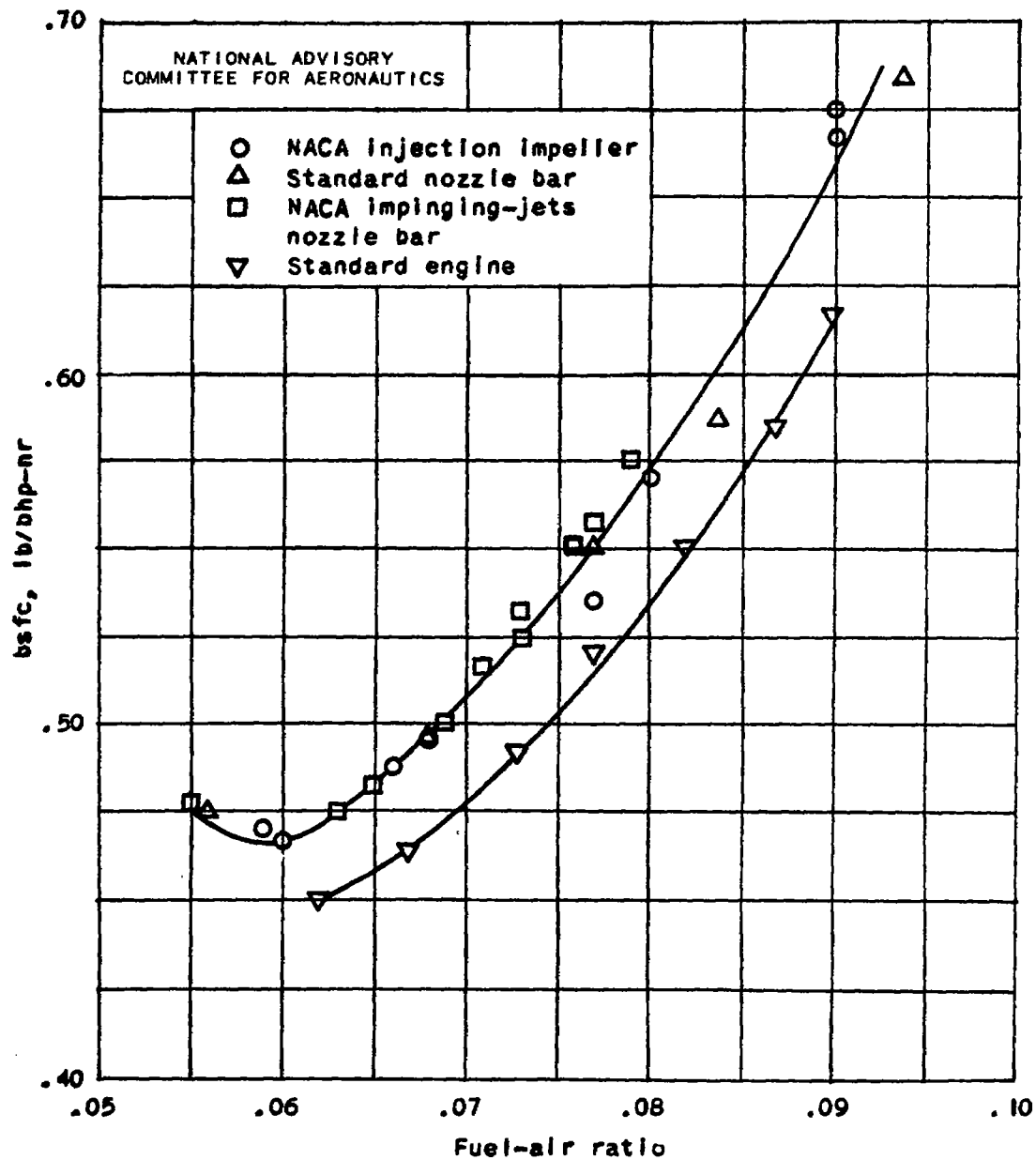


Figure 12. - Brake specific fuel consumption at 1200 brake horsepower for standard nozzle-bar injection of gasoline and for safety-fuel injection by NACA injection impeller, NACA impinging-jets nozzle bar, and standard nozzle bar.